Five-Segment Resource Circulation Model Using Shortcut Transitions

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Abstract — Understanding resource circulation is vital for addressing environmental problems. In the past, resource circulation between the Earth's natural and societal spaces was balanced. However, due to recent mass production, consumption, and disposal in societal space, such resource circulation is no longer balanced. In this paper, we further develop the domain transition probability model for resource circulation that we proposed previously, and suggest a new five-segment resource circulation model that can consider shortcuts between the domains within it. This model can consider a supply chain consisting of manufacturers and suppliers in societal space, and can be used to analyze the effects of environmental activities on societal space. This model provides several suggestions about the impacts of activities, such as artificial waste purification, recycling, and inventory disposal, on resource circulation, which are based on the results of simple numerical simulations. This model also indicates towards new directions for environmental activities that can improve the Earth's environment.

Keywords — resource circulation, Earth environment, reduce, reuse, recycle, domain transition

I. INTRODUCTION

There is a deep, underlying connection between resources and environmental problems. Until now, the human population has utilized the Earth's resources for mass production, consumption, and disposal of industrial products and food, supporting prosperous civilizations. However, a closer examination of resource circulation reveals that the ever-expanding population is putting pressure on the Earth in several ways, leading to environmental problems. Ohno et al. previously proposed a conceptual resource circulation model [1]. To quantitatively analyze the model, it was further developed into a resource circulation domain transition probability model [2], and was later expanded [3] using the 3R matrix and including the 3R activities, i.e., reducing, reusing, and recycling waste. These resource circulation models were based on one that describes resource circulation from a macroscopic perspective in natural and societal space as transitions between four domains, in which resources transition from the resource to the production domain, then to the consumption and waste domains, and then back to the resource domain. Furthermore, Sakai et al. [4] proposed a five-segment resource circulation model, in which production is divided into the manufacturer and supplier domains. This model enables the supply chain to be described. Yamashita et al. [5] proposed a model that not only transitions between neighboring areas, but also enables shortcut transitions between separated areas.

In this research, we apply shortcut transitions to the five-segment model, presenting a novel system. Based on this model, we analyze and discuss factors, such as the transition from each domain to the resource and the waste domains, and the diversity of recycling methods. For transitions to the resource domain, we discuss the effects of artificial purification, in which resources directly transition from consumption to the resource domain. For transitions to the waste domain, we discuss the impact of disposing of unsold items. Furthermore, we also discuss the different effects of recycling on transitions from consumption to the other domains, and determine the impact of environmental activities on resource circulation. From this model, it is possible to compare various states using simple numerical examples, and the extent of the effects of environmental activities in societal spaces can be compared. The effect on the environmental activities of companies within the supply chain can be determined by simulation.

In the following sections, we describe the conceptual resource circulation model, and then explain the domain transition probability model (3R model, five-segment model). Furthermore, we describe the model proposed in this study, and use it to simulate and confirm the effect of environmental activities.

II. CONCEPTUAL RESOURCE CIRCULATION MODEL

Ohno et al. [1] studied the need for environmental conservation efforts, and proposed the conceptual resource circulation model presented in **Figure 1**. In this model, global resource circulation was described as a process involving transitions between domains, such that resources transition from the resource domain to the production, consumption, and waste domains, and then back to the resource domain. As shown in the conceptual model presented in **Figure 1**, in the societal space, producers (production domain) and consumers (consumption domain) take in resources from the natural space to attain value in alignment with their own goals, and expel these resources back to the natural space after their value has been consumed. In contrast, the principles of purpose, including the attainment of profit and satisfaction, do not exist in the natural space, and this space consists of the resource, from which resources are taken by production inside the societal space, and waste domains, which receives waste [6]. We proposed that the production domain in **Figure 1** should be divided into a parts production domain, containing suppliers, and a finished product production domain, containing manufacturers [7, 8]. This proposal allows synchronization and de-synchronization between these domains to be considered. This revised model is shown in **Figure 2**. Comparing this with **Figure 1**, this model contains five segments, in which resources move from the resource domain to the parts production, finished product, consumption, and waste domains, and then back to the resource domain This model enables researchers to describe a supply chain that includes suppliers and manufacturers.

From the conceptual models in **Figures 1** and **2**, a large portion of the environmental problems we are facing is based in the waste domain. The natural space has historically maintained a balance between the resource and waste domains through self-purification. However, with the advent of the industrial revolution, the natural purification process could no longer keep up with the speed of intake and expulsion, and the balance was lost. The true essence of environmental problems we face today lies in the loss of balance between the resource and waste domains in the natural space due to the shrinkage of the resource domain and enlargement of the waste domain.

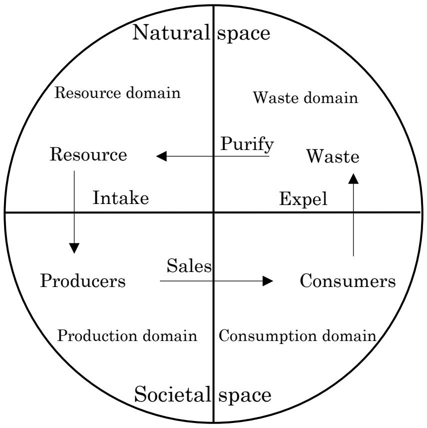

Figure 1. Conceptual resource circulation model

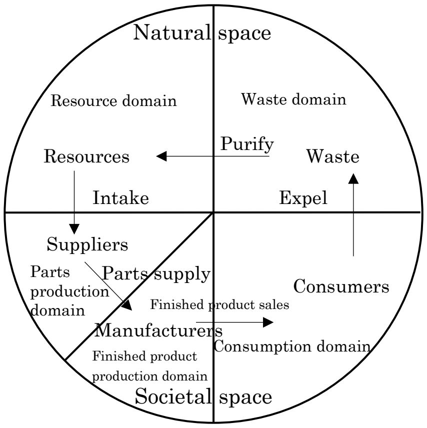

Figure 2. Five-segment resource circulation model

It is, therefore, necessary to use artificial purification to supplement natural purification, which is insufficient on its own, to allow resources to transition from the waste to the resource domain in the natural space. Artificial purification suggests that resources take a direct shortcut from the consumption to the resource domain without passing through the waste domain in **Figure 1**. Yamashita et al. [5] proposed a new model that adds shortcuts to the model shown in **Figure 1**. In contrast to the model proposed by Yamashita, our proposed model can consider shortcuts related to the parts and finished product production domains that consist of suppliers and manufacturers.

To discuss the environmental activities of companies that constitute the supply chain in more detail, it is necessary to focus on shortcuts, such as activities to discard unsold food items or reuse used PET bottles as raw materials for other products. If shortcuts can be considered, it will be possible to construct models that can reflect environmental activities in complex societal space more accurately.

III. DOMAIN TRANSITION PROBABILITY MODEL FOR RESOURCE CIRCULATION

To quantitatively describe the transitions between the four domains (resource, production, consumption, waste) in the conceptual model presented in **Figure 1** from a macroscopic perspective, Yamashita et al. [2] proposed the domain transition probability model for resource circulation. In addition, Sakai et al. [4] described transitions between five domains (resource, parts production, finished product production, consumption, waste) using a five-segment domain transition probability model. In this model, the proportions of the components in each of the domains (resource s_1, parts inventory s_2, finished inventory s_3, in-use s_4, and waste proportions s_5) can be quantitatively described using a state vector $\boldsymbol{S} = (s_1, s_2, s_3, s_4, s_5)$ that transitions according to the domain transition probability matrix $\boldsymbol{P} = (p_{ij})$, as shown in Equation (1).

Here, elements p_1, p_2, p_3, p_4, and p_5 in the domain transition probability matrix represent the probability of transition from the resource to the parts production domain, from the parts production to the finished products production domain, from the finished products production to the consumption domain, from the consumption to the waste domain, and from the waste to the resource domain. p_1 is the intake rate, p_2 is the parts supply synchronization rate, p_3 is the finished products sales synchronization rate, p_4 is the expulsion rate, and p_5 is the natural purification rate.

$$P = \begin{pmatrix} 1-p_1 & p_1 & 0 & 0 & 0 \\ 0 & 1-p_2 & p_2 & 0 & 0 \\ 0 & 0 & 1-p_3 & p_3 & 0 \\ 0 & 0 & 0 & 1-p_4 & p_4 \\ p_5 & 0 & 0 & 0 & 1-p_5 \end{pmatrix} \quad (1)$$

where $\boldsymbol{S}(t)$ represents the state vector at time t. If we assume that the domain transition probability matrix $\boldsymbol{P}$ is constant based on time t, then $\boldsymbol{S}(t+1)$, which is the state vector at time $t+1$, can be represented by the following equation.

$$\boldsymbol{S}(t+1) = \boldsymbol{S}(t) \cdot \boldsymbol{P} \qquad (2)$$

where $\boldsymbol{S}^*$ represents the state vector $\boldsymbol{S}(\infty)$ after these domain transitions are repeated infinitely ($t \to \infty$). The value of $\boldsymbol{S}(t)$ will form a Markov chain and converge with the steady-state state vector $\boldsymbol{S}^*$, which satisfies Equation (3) if state vector $\boldsymbol{S}(t)$ converges without periodicity [9]. The steady-state state vector $\boldsymbol{S}^*$ can be calculated by solving the five-dimensional first-order equations in Equation (3).

$$\boldsymbol{S}^* = \lim_{t \to \infty} \boldsymbol{S}(0) \cdot \boldsymbol{P}^t = \boldsymbol{S}^* \cdot \boldsymbol{P} \qquad (3)$$

$$R = \begin{pmatrix} r_1 & -r_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & r_3 & r_4 & r_2 & -r_2-r_3-r_4 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (4)$$

Here, r_1 : Reduce rate, r_2 : Reuse rate, r_3 : Recycle rate (consumer to parts), r_4 : Recycle rate (consumer to finished product)

Furthermore, Yamashita et al. [3] focused on the 3R activities of "reduce, reuse, and recycle", which are common measures for improving the environment, and described the effect using the matrix $\boldsymbol{R}$ shown in Equation (4). If we include Equation (4) in the five-segment resource circulation domain transition probability model described earlier, then Equation (3) can expand, as shown in Equation (5) (five segment domain transition probability model using the 3R matrix). Therefore, if we replace matrix $\boldsymbol{P}$ in Equation (3) by matrix $\boldsymbol{P} + \boldsymbol{R}$, then the steady-state state vector $\boldsymbol{S}^*$ can be calculated by solving the five-dimensional first-order equations in Equation (5), similar to Equation (3).

$$\boldsymbol{S}^* = \lim_{t \to \infty} \boldsymbol{S}(0) \cdot (\boldsymbol{P} + \boldsymbol{R})^t = \boldsymbol{S}^* \cdot (\boldsymbol{P} + \boldsymbol{R}) \qquad (5)$$

IV. MODEL PROPOSED IN THIS PAPER

In this paper, we aim to include shortcut domain transitions in the basic model, which were not considered in the five-segment domain transition probability model proposed by Sakai et al. [4]. Here, we considered shortcut domain transitions other than those shown in **Figure 2**, which are those from the resource to the parts production, finished products production, consumption, and waste domains, and then back to the resource domain. First, we assume that there is a shortcut from the consumption to the resource domain, and hereby refer to it as the consumption-resources shortcut. This shortcut refers to the transition in which resources move from the consumption to the resources domain without passing through the waste domain and gain additional potential. This process is referred to as artificial purification, therefore, this shortcut is referred to as the artificial purification shortcut. A similar shortcut to the resource domain is that from the finished product production domain (hereafter referred to as the finished product-resource shortcut). This shortcut covers the transition in which unsold finished products move to the resource domain through artificial purification. Another similar shortcut to the resource domain is that from the parts production domain. This transition is not actually a shortcut, but represents the “reduce” portion of the 3R activities.

Next, we consider shortcuts to the waste domain. Shortcuts from the parts production and the finished product production to the waste domain exist (hereafter referred to as the parts-waste and the finished product-waste shortcuts, respectively). A similar shortcut to the waste domain is that from the consumption domain to. This is a transition between neighboring domains (hereafter referred to as the consumption-waste transition).

In addition, from the recycling perspective, there is also a shortcut from the consumption to the parts production domain (hereafter referred to as the consumption-parts shortcut), and a transition from the consumption to the finished product production domain (hereafter referred to as the consumption-finished product transition).

In this paper, we focus on the shortcuts and domain transitions described above, and propose a domain transition analysis model for resource circulation, in which we introduce the shortcut matrix ***U*** in Equation (6) in addition to the domain transition probability matrix ***P*** in Equation (1) and the 3R matrix ***R*** in Equation (4).

$$U = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -u_3 & 0 & 0 & u_3 \\ u_2 & 0 & -u_2-u_4 & 0 & u_4 \\ u_1 & 0 & 0 & -u_1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (6)$$

where u_1 : Resource-consumption (artificial purification) shortcut rate,
u_2 : Finished product-resource shortcut rate,
u_3 : Parts-waste shortcut rate,
u_4 : Finished product-waste shortcut rate

where, considering the shortcut matrix ***U*** in Equation (6), the matrix $\boldsymbol{P} + \boldsymbol{R}$ in Equation (5) can be replaced with $\boldsymbol{P} + \boldsymbol{R} + \boldsymbol{U}$. Then, the steady-state state vector $\boldsymbol{S}^*$ can be represented as shown in Equation (7):

$$\boldsymbol{S}^* = \lim_{t\to\infty} \boldsymbol{S}(0)\cdot(\boldsymbol{P}+\boldsymbol{R}+\boldsymbol{U})^t = \boldsymbol{S}^*\cdot(\boldsymbol{P}+\boldsymbol{R}+\boldsymbol{U}) \quad (7)$$

$$E = \begin{pmatrix} e_{11} & e_{12} & 0 & 0 & 0 \\ 0 & e_{22} & e_{23} & 0 & e_{25} \\ e_{31} & 0 & e_{33} & e_{34} & e_{35} \\ e_{41} & e_{42} & e_{43} & e_{44} & e_{45} \\ e_{51} & 0 & 0 & 0 & e_{55} \end{pmatrix} \quad (8)$$

where $e_{11} = 1 - p_1 + r_1,\ e_{12} = p_1 - r_1,$
$e_{22} = 1 - p_2 - u_3,\ e_{23} = p_2,\ e_{25} = u_3,$
$e_{31} = u_2,\ e_{33} = 1 - p_3 - u_2 - u_4,$
$e_{34} = p_3,\ e_{35} = p_4,\ e_{41} = u_1,\ e_{42} = r_3,\ e_{43} = r_4,$
$e_{44} = 1 - p_4 + r_2 - u_1,\ e_{45} = p_4 - r_2 - r_3 - r_4,$
$e_{51} = p_5,\ e_{55} = 1 - p_5,$

In this paper, the matrix in Equation (7) is $\boldsymbol{P} + \boldsymbol{R} + \boldsymbol{U} = \boldsymbol{E}$. Matrix E is referred to as the environmental transition probability matrix. Substituting these expressions into Equation (7) gives five equations. Considering that the sum of the elements in the steady-state vector $\boldsymbol{S}^* = (s_1^*, s_2^*, s_3^*, s_4^*, s_5^*)$ is equal to 1, the system of equations can be solved to provide the unknown variables required for Equations (9) to (13). Substituting Equations (14) to (17) into these expressions allows us to estimate the steady-state vector.

$$s_1^* = B\cdot s_4^* \quad (9)$$
$$s_2^* = A\cdot s_4^* \quad (10)$$
$$s_3^* = C\cdot s_4^* \quad (11)$$
$$s_4^* = 1\ /\ (A + B + C + \mathrm{D} + 1) \quad (12)$$
$$s_5^* = D\cdot s_4^* \quad (13)$$

where $A = \{(1 - e_{33})(1 - e_{44}) - e_{34}\cdot e_{43}\}\ /\ e_{23}\cdot e_{34}$ (14)
$B = \{A\cdot(1 - e_{22}) - e_{42}\}\ /\ e_{12}$ (15)
$C = (A\cdot e_{23} + e_{43})\ /\ (1 - e_{33})$ (16)
$D = \{B\cdot(1 - e_{11}) - C\cdot e_{31} - e_{41}\}\ /\ e_{51}$ (17)

V. ANALYSIS WITH A SIMPLE NUMERICAL EXAMPLE

The model proposed in this paper enables the inclusion of shortcut domain transitions into the five-segment domain transition probability model using the 3R matrix described above. Below, we present a simple numerical example of the proposed model, and estimate the steady-state state vector $\boldsymbol{S}^*$ considering the shortcut domain transitions.

Basic Numerical Example

The following conditions are applied to the basic numerical example:

- The supply of parts from the suppliers to the manufacturers and the sale of products from the manufacturers to the consumers are synchronized (parts supply synchronization rate (p_2) = 1, finished product sales synchronization rate (p_3) = 1).
- The rate of recycling from the consumers to the suppliers (r_3), and the rate of recycling from the consumers to the manufacturers (r_4) are equal ($r_3 = r_4 = 0.005$).
- The reduce (r_1), consumption-resource (artificial purification) shortcut (u_1), and finished product-resource shortcut rates (u_2) are equal ($r_1 = u_1 = u_2 = 0.001$).
- The expulsion (p_4), parts-waste shortcut (u_3), and finished product-waste shortcut rates (u_4) are 0.1, 0.01, and 0.01, respectively.

Using the above information, the values of the domain transition probability matrix $\boldsymbol{P}$, the 3R matrix $\boldsymbol{R}$, and the shortcut matrix $\boldsymbol{U}$ in this basic numerical example are the following:

where $p_1 = 0.01$, $p_2 = 1$, $p_3 = 1$, $p_4 = 0.1$, $p_5 = 0.0001$, $r_1 = 0.001$, $r_2 = 0.01$, $r_3 = 0.005$, $r_4 = 0.005$, $u_1 = 0.001$, $u_2 = 0.001$, $u_3 = 0.01$, $u_4 = 0.01$

$$P = \begin{pmatrix} 0.99 & 0.01 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0.9 & 0.1 \\ 0.0001 & 0 & 0 & 0 & 0.9999 \end{pmatrix}, \quad R = \begin{pmatrix} 0.001 & -0.001 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0.005 & 0.005 & 0.01 & -0.02 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad U = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -0.01 & 0 & 0 & 0.01 \\ 0.001 & 0 & -0.011 & 0 & 0.01 \\ 0.001 & 0 & 0 & -0.001 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Table 1 shows the steady-state state vector $\boldsymbol{S}^*$ that was calculated in this basic numerical example.

Table 1 Steady-state vector in the basic numerical example

Stead-state vector Numerical example	Resource amount S_1^*	Parts inventory amount S_2^*	Finished products inventory amount S_3^*	In-use amount S_4^*	Waste amount S_5^*	Total inventory amount S_2^*+S_3^*
Basic numerical example	0.0111181	0.0001051	0.0001099	0.0012075	0.9874595	0.0002149

Next, we changed the domain transition probability values of the transitions, including the shortcuts, and compared the effects of environmental activities. In numerical examples 1-A to 1-C, we verify the effects of environmental activities that cause resources to transition directly to the resource domain. In numerical examples 2-A to 2-C, we verify the effects of reducing the amount of material that directly transitions into the waste domain. In numerical examples 3-A to 3-B, we verify the effects of recycling activities.

(Numerical Example 1)

- We verified the effects of increasing the value of each of the reduce (r_1), consumption-resource (artificial purification) shortcut (u_1), and finished product-resource shortcut rates (u_2) by 0.001.

(Numerical Example 1-A)
Reduce rate (r_1) increased by 0.001

$$R = \begin{pmatrix} 0.002 & -0.002 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0.005 & 0.005 & 0.01 & -0.02 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

(Numerical Example 1-B)
Consumption-resource (artificial purification) shortcut rate (u_1) increased by 0.001

$$U = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -0.01 & 0 & 0 & 0.01 \\ 0.001 & 0 & -0.011 & 0 & 0.01 \\ 0.002 & 0 & 0 & -0.002 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

(Numerical Example 1-C)
Finished product-resource shortcut rate (u_2) increased by 0.001

$$U = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -0.01 & 0 & 0 & 0.01 \\ 0.002 & 0 & -0.012 & 0 & 0.01 \\ 0.001 & 0 & 0 & -0.001 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

(Numerical Example 2)

- We verified the effect of reducing the value of the expulsion (p_4), parts-waste shortcut (u_3), and finished product-waste shortcut rates (u_4) by 0.01.

(Numerical Example 2-A)
Expulsion rate (p_4)
decreased by 0.01

$$P = \begin{pmatrix} 0.99 & 0.01 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0.91 & 0.09 \\ 0.0001 & 0 & 0 & 0 & 0.9999 \end{pmatrix}$$

(Numerical Example 2-B)
Parts-waste shortcut rate
(u_3) reduced by 0.01

$$U = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0.001 & 0 & -0.011 & 0 & 0.01 \\ 0.001 & 0 & 0 & -0.001 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

(Numerical Example 2-C)
Finished product-waste shortcut
rate (u_4) reduced by 0.01

$$U = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -0.01 & 0 & 0 & 0.01 \\ 0.001 & 0 & -0.001 & 0 & 0 \\ 0.001 & 0 & 0 & -0.001 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

(Numerical Example 3)

- We changed the values of the recycle rate from the consumers to the suppliers (r_3), and that from the consumers to the manufacturers (r_4) to r_3 =0.01, r_4 =0, and to r_3 =0, r_4 =0.01, and compared the two cases.

(Numerical Example 3-A)
Rate of recycling from consumers to suppliers (r_3) = 0.01
Rate of recycling from consumers to manufacturers (r_4) = 0

$$R = \begin{pmatrix} 0.001 & -0.001 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0.01 & 0 & 0.01 & -0.02 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

(Numerical Example 3-B)
Rate of recycling from consumers to suppliers (r_3) = 0
Rate of recycling from consumers to manufacturers (r_4) = 0.01

$$R = \begin{pmatrix} 0.001 & -0.001 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0. & 0.01 & 0.01 & -0.02 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

We calculated the environmental transition probability matrix value E (= $\boldsymbol{P} + \boldsymbol{R} + \boldsymbol{U}$) and $\boldsymbol{S}^*$ for each of the numerical examples. The results are shown in **Tables 2** to **4**.

Table 2 Steady-state vectors in numerical examples 1-A to 1-C

Steady-state vector Numerical example	Resource amount S_1^*	Parts inventory amount S_2^*	Finished products inventory amount S_3^*	In-use amount S_4^*	Waste amount S_5^*	Total inventory amount S_2^*+S_3^*
1-A	0.0124906	0.0001049	0.0001097	0.0012058	0.9860890	0.0002146
1-B	0.0112508	0.0001062	0.0001110	0.0012070	0.9873249	0.0002173
1-C	0.0111302	0.0001052	0.0001099	0.0012074	0.9874473	0.0002150

Table 3 Steady-state vectors in numerical examples 2-A to 2-C

Steady-state vector Numerical example	Resource amount S_1^*	Parts inventory amount S_2^*	Finished products inventory amount S_3^*	In-use amount S_4^*	Waste amount S_5^*	Total inventory amount S_2^*+S_3^*
2-A	0.0111353	0.0001061	0.0001117	0.0013793	0.9872676	0.0002178
2-B	0.0111195	0.0001062	0.0001111	0.0012204	0.9874428	0.0002173
2-C	0.0111196	0.0001051	0.0001111	0.0012212	0.9874430	0.0002162

Table 4 Steady-state vectors in numerical examples 3-A and 3-B

Steady-state vector Numerical example	Resource amount S_1^*	Parts inventory amount S_2^*	Finished products inventory amount S_3^*	In-use amount S_4^*	Waste amount S_5^*	Total inventory amount S_2^*+S_3^*
3-A	0.0111180	0.0001110	0.0001098	0.0012067	0.9874545	0.0002208
3-B	0.0111183	0.0000991	0.0001099	0.0012082	0.9874645	0.0002090

In **Table 2**, numerical example 1-A (reduce) has the highest resource value and the lowest waste value of the three cases. The results show that reducing waste has a positive effect on the natural space. In addition, this example also has the lowest inventory value (S_2^*+S_3^*), indicating a highly efficient supply chain. These results demonstrate that reducing waste is the most effective environmental activity of the three numerical examples, in which resources are moved directly to the resource domain. Activities to reduce resource intake by suppliers are more effective than those that require manufacturers and consumers to return products to resources by artificial purification.

In **Table 3,** numerical example 2-A (reduce the transition from the consumption to the waste domain) has the highest resources value and the lowest waste value of the three cases. The results demonstrate that increasing the transition from the consumption to the waste domain has a positive effect on the natural space. however, the total inventory value (S_2^*+S_3^*) is at its highest in this example, indicating that the supply chain is highly inefficient. The lowest total inventory value in **Table 3** occurs for numerical example 2-B (reduce the transition from the finished product production to the waste domain). This result indicates that companies became more efficient when the manufacturers moved unsold inventory to the waste domain. Therefore, reduction of unsold food waste, for example, leads to inventory reduction throughout the supply chain.

In **Table 4**, numerical example 3-A (focus recycling activities on suppliers) has a larger total inventory value. This shows that resources remain in the societal space for longer when they are recycled by suppliers, rather than if they had been recycled by manufacturers, and that movement of resources to the waste domain is slow. However, numerical example 3-B (focus recycling activities on manufacturers) has a smaller total inventory value and larger resource and in-use values. This situation is relatively desirable, because, rather than recycling iron from scrapped cars to suppliers, recycling good-quality parts to manufacturers will result in favorable results overall.

VI. CONCLUSION

In this paper, we added shortcut domain transitions to a five-segment domain transition probability model using the 3R matrix, and compared various situations through simple numerical simulation. We verified the relative magnitudes of the impacts of different environmental activities on societal space. Based on the model presented here, reduction activities by suppliers are more effective than artificial purification conducted by manufacturers and consumers, and the reduction of unsold food waste can effectively reduce the inventory of the entire supply chain. It was found that recycling iron as parts rather than as scraps would be preferable. As the simulations were based on numerical examples set by the authors, they may deviate from actual events in society. From understanding the limitations of this research, in the future, we would like to conduct simulations incorporating real data. We hope that the results of this research will assist companies in the supply chain during the development of their environmental activities.

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BIOGRAPHY

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