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INTEGRATION OF ENVIRONMENTALLY-CONSCIOUS TRANSPORTATION MODEL WITH LIFE CYCLE ASSESSMENT IN REVERSE LOGISTICS

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Abstract. *In the supply chain realm, Reverse Logistics (RL) is a feasible strategy to comply with environmental regulations because it can contribute to increasing resource-efficiency by recollecting and refurbishing leftover wastes. However, RL unavoidably causes environmental burdens due to the uses of transportation vehicles. Thus, it is critical to develop an environmentally-conscious transportation model that can improve resource-efficiency through reducing subsidiary materials under given circumstance. Additionally, such the model's environmental performance should be quantitatively analyzed through a common methodology, Life Cycle Assessment (LCA). However, the dynamic, various and complex characteristics in RL are major obstacles of the application of LCA, which is mainly targeted at static product systems. This paper presents: the proposition of an environmentally-conscious transportation model, the design of an integration method of LCA with RL, and the application of LCA to a case of home appliances in an RL network.*
Keywords: Reverse logistics, Life cycle assessment, Green supply chain management, Environmental consciousness

1. **Introduction.** As environmental policies are being enforced, they naturally call for extending the manufacturer's domain of responsibility from Begin-of-Life (BOL; design and production) to Middle-of-Life (MOL; distribution and in-use) and End-of-Life (EOL; disposal). Accordingly, this trend of extension is influencing the supply chain realm, and thus the concept of green supply chain is drawing interest from stakeholders of Supply Chain Management (SCM) [1]. Reverse Logistics (RL) noteworthily becomes a feasible strategy toward green SCM because it contributes to increasing resource-efficiency through remanufacturing, recycling and reusing of products expired from the in-use phase [2].

RL is the process of planning, implementing and controlling the efficient flow of raw materials, in-process inventory, finished goods and relevant information from the point of consumption to origin [3]. RL goes backwards in that discarded products are re-incorporated within the logistics network; on the other hand, generic logistics goes forwards. However, RL inevitably imposes environmental burdens. There are known facts that fossil fuel consumed by vehicles causes Green House Gases (GHG), and packing material incineration emits hazardous substances. Therefore, RL, in itself, should consider more greenable, i.e., environmentally-conscious, activities to minimize environmental burdens. It is critical

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to develop greenable transportation models that can improve resource-efficiency through reducing subsidiary packaging or transportation vehicle usage.

Most literature on RL has been made in terms of network design, vehicle routing and scheduling and optimal location. [4,5] developed simulation models to analyze the suitable allocation of facility and to collect EOL appliances. [6] proposed a two-stage stochastic programming to determine optimal facility locations and flows. [7] presented solutions for transportation problems related to vehicle routing and scheduling. [8] dealt with a dual-depot heterogeneous vehicle routing problem with simultaneous delivery and pick-up. Only a few studies including [9,10] have strived to applying environmental assessment, respectively, into recollecting different beverage packaging systems and recycling refrigerators under different scenarios. Their efforts help understand comparative quantification of environmental impacts in the product applications; however, they limit in providing an efficient way of reducing the uses of subsidiary packages and transportation vehicles within the RL network.

One primary action for developing greenable transportation models is allegedly to assess the environmental impacts of these models using a quantifiable methodology [11]. The main reason is that any prediction or optimization cannot be achieved without assessment of the current context. Life Cycle Assessment (LCA) is a commonly used methodology for such the purpose. LCA is the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout lifecycle [12]. However, it is difficult to integrate the LCA methodology with RL-relevant models. LCA was originally targeted at static product systems, whereas RL models have more complexity, dynamics and variety along with a degree of uncertainty. In RL, various scenarios accompanied with many assumptions can influence LCA results due to floating periodic or regional factors. A functional unit for delivering, packaging and loading can be changeable. Thus, the uncertainty due to the complexity and dynamics interrupts a quantified assessment, and a service-oriented LCA accommodating RL models should be developed.

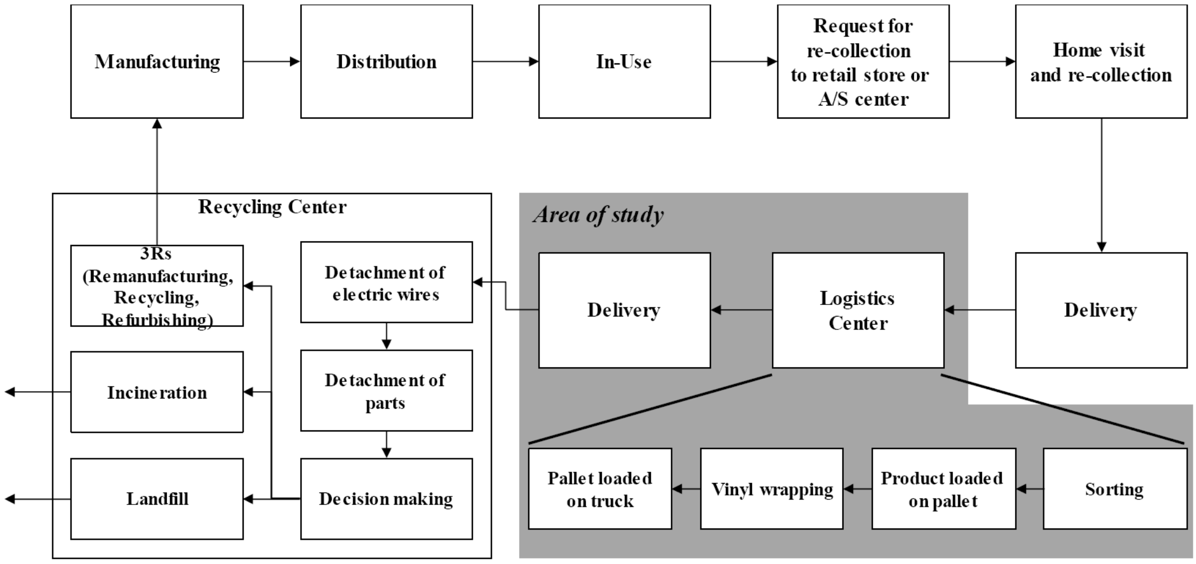
In the above, this paper proposes a greenable transportation model for reducing the uses of subsidiary packaging materials in the RL network. This paper also suggests an RL-integrated LCA procedure to guide effective environmental assessment for RL-relevant models. This paper presents a case study that compares environmental impacts of the proposed model with those of a conventional model in the re-collection process of home appliances in South Korea. The paper is organized as follows. Section 2 explains the conventional and greenable transportation models. Section 3 describes the integration of the LCA procedure with RL. Section 4 presents a case study. Section 5 concludes the paper with closing remarks.

2. **Transportation Models.** Section 2.1 explains the conventional transportation model. Section 2.2 presents the greenable transportation model.

2.1. **Traditional transportation model.** Figures 1(a) and 1(b), respectively, show the method and process of the conventional transportation model (As-Is model). Re-collected products are sorted into categories of products at a logistics center. The categorized products are then stacked onto a unit loading vessel – pallet – for efficient transportation. These products on a pallet are packed to prevent product breakage caused by tip over and fall. For this purpose, vinyl resin wrap is wound twice around the sides of the product stack.

2.2. **Environmentally-conscious transportation model.** From the environmental view, the main problem of the As-Is model is that vinyl materials cause resource consumption, which has the potential to release air pollutants or infusible wastes. To solve this problem, the Unit Load System (ULS) that utilizes a steel-barred cubic container

(a) Vinyl wrapping



(b) Flow diagram

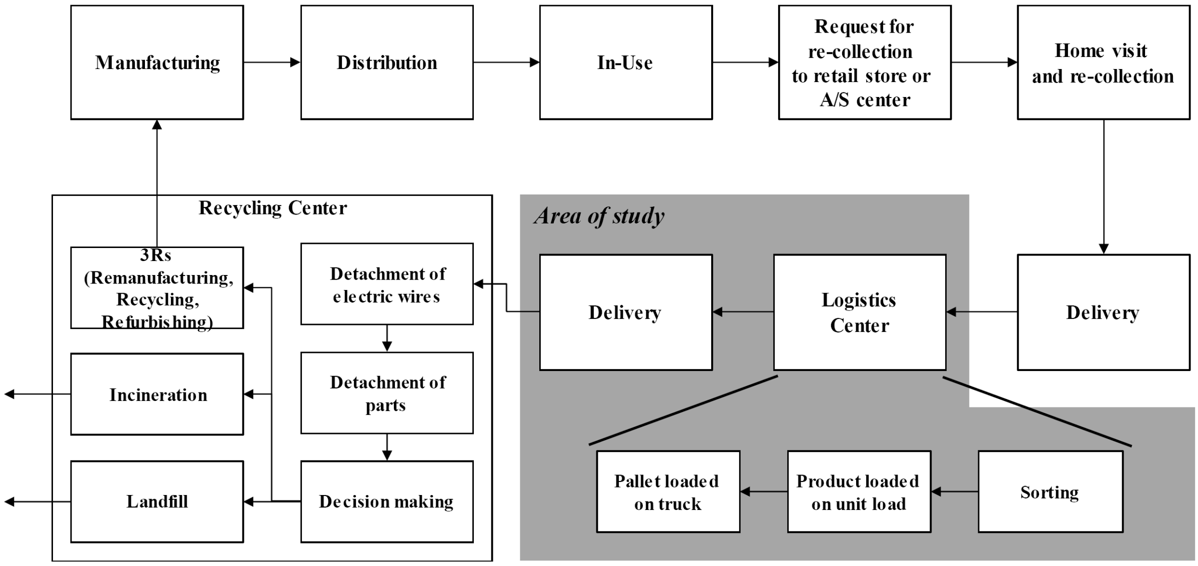
FIGURE 1. Method and process of the conventional transportation model

is proposed, as shown in Figure 2(a). Figure 2(b) illustrates the process of the greenable transportation model (To-Be model). This model enables the elimination of the wrapping operation and improves (un-)loading efficiency through the standardization of delivery units, that is, the vessel units used for loading the appliances packaged at a logistics center.

3. **Integration of LCA with Reverse Logistics.** LCA helps calculate the environmental impacts of the given two transportation models, and therefore arrive at the best model from the ecological perspective. However, it is not easy to apply LCA into RL-relevant models. Section 3.1 identifies causes and problems in the application of LCA to RL-relevant models, and Section 3.2 describes an RL-integrated LCA procedure.

3.1. **Problem.** As addressed in Section 1, RL-relevant models have complexity, dynamics and variety. As these characteristics result from that RL is a service system, they inevitably make it difficult to apply LCA, which was mainly targeted for static product systems [12]. Bill-of-Material (BOM) configuring the product informs physical components and their containing materials needed to measure their physical metrics (e.g., mass, area and volume), which facilitate LCA studies [12]. Whereas, LCA for service systems should build upon designated circumstances and scenarios because service systems are typically designed regardless of measuring physical metrics. Thus, the application of LCA into RL-relevant models requires the design and use of a service-oriented LCA approach. The identification of causes and problems in the service-oriented approach should be preceded, and Table 1 presents primary causes and problems.

(a) Unit-load



(b) Flow diagram

FIGURE 2. Method and process of the environmentally-conscious transportation model

TABLE 1. Causes and problems of LCA in reverse logistics relevant models

ID	Causes	Problems
1	Recollection of multi-types of wasted products	- Difficulty in defining a functional unit - Change in the number of products loaded in a unit-load - Difficulty in use of the unique metric
2	Periodic fluctuation of products recollected	- Inaccurate calculation of the number of products recollected - Addition of alternative pathways due to over-capacity in a primary recycling center
3	Variety of transportation vehicles	- Variety of capacity of transportation vehicles - Difference in fuel efficiency of transportation vehicles
4	Difficulty in data collection	- Increase of time and cost for LCA study - Difficulty in ensuring data quality

3.2. **Method for LCA integration with reverse logistics.** It is necessary to integrate reasonable considerations into the generic LCA procedure to resolve the identified problems as explained in Table 1. The direction for this integration needs to include that: 1) multiple scenarios accommodated for periodic fluctuations are structurally designed, thereby leading to determine the number of wasted products and the operations of transportation vehicles, 2) the functional unit and the metric, which are the basis of LCA study,

Table 2. Considerations for LCA integration with reverse logistics

ID	Considerations
1	- Use of delivery unit (unit-load), instead of product unit, for functional unit - Unification of the number of loaded products per product-type - Use of ton*km metric in case of transportation
2	- Decision on the number of products recollected with regard to periods - Addition of alternative pathways inside system boundary
3	- Investigation of actual transportation vehicles
4	- Use of referential data certified in the region where the system locates

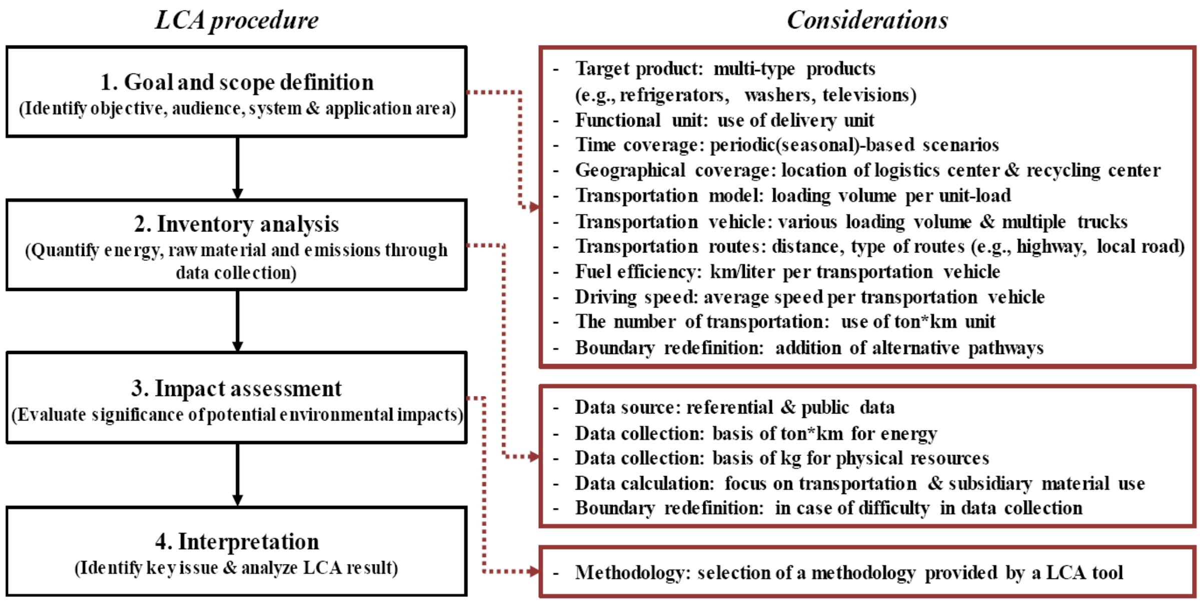


Figure 3. A service-oriented LCA method for reverse logistics relevant models

are identified in a unique way, and 3) public and referential databases are used to ensure data quality and facilitate data collection. Table 2 presents available considerations for the causes and problems in Table 1. Figure 3 shows the service-oriented LCA method where the generic LCA procedure and the considerations are merged.

4. **Case Study.** This section presents a case study to analyze the significance of environmental impacts in the two transportation models presented in Section 2. An LCA software, TOTAL provided by the Korean government, is used to execute the LCA study. Section 4.1 clarifies a given scenario, and Section 4.2 describes the LCA study.

4.1. **Scenario.** The overall scenario is that waste appliances are re-collected at a logistics center and delivery units loading the wastes are transported to recycling centers managed by provincial governments. Trucks pick up waste appliances including televisions, washers and refrigerators from customer homes, and carry them to a logistic center. The hot-season associated with a moving season continues from July to September, and collects one and a half time of the number of appliances recollected in the off-season. In the logistics center, each pallet and ULS is capable of containing four refrigerators, twelve washers or twelve televisions at a time. The average monthly numbers (#) of appliances re-collected, and the average monthly numbers of delivery units are below.

Number of waste units in off-season: $\{$*refrigerator, washer, television*$\}$ = $\{$*408, 332, 308*$\}$

Number of waste units in hot-season: $\{$*628, 432, 452*$\}$

Number of delivery units in off-season: {102, 28, 26}
Number of delivery units in hot-season: {157, 36, 38}

The packaged delivery units are transported to a recycling center A, which is managed by Province α where the logistics center locates. The maximum capacity of center A is 180 delivery units per month, and hence residual delivery units should be transported to the alternative recycling center B, located in nearby Province β in the hot-season.

Trucks loading 2.5 or 5 ton weights traverse local roads or highways, operated respectively from the logistics center to recycling center A or B: 35.5 km (one-way distance), 71 km (round-trip distance), 40 minute (average one-way time) and 53.3 km/hour (average velocity); 161 km, 323.4 km, 140 minute and 69.3 km/hour. A 5-ton truck is the primary vehicle used for transporting the units to recycling center A, and a 2.5-ton truck is the supplementary vehicle used for residual delivery units. Another 5-ton truck is a unique vehicle for connecting with recycling center B. A 2.5-ton truck can load two delivery units with a diesel fuel efficiency of an average 7 km/liter; whereas, a 5-ton truck loads four delivery units with that of an average 5 km/liter. Table 3 shows these trucks' operations and the average mass and distance on monthly transportations.

Table 3. Monthly transportation operations

Case	Truck (ton)	Destination	# of operations	# of delivery units	Ton*km	Total ton*km
Off-season	2.5	A	18	36	3195	13845
	5	A	30	120	10650	
Hot-season	2.5	A	30	60	5325	36996
	5	A	30	120	10650	
	5	B	13	52	21021	

4.2. **LCA study.**

(1) Goal and scope definition: the goal of LCA is to assess quantitative environmental impacts of four different scenarios (As-Is off, As-Is hot, To-Be off, or To-Be hot cases). A function is delivering waste appliances from a logistic center to recycling centers. The functional unit is set to be a delivery unit presented with a pallet or ULS. The reference flow is to deliver four refrigerators, twelve washers or twelve televisions on a delivery unit. The system boundary is identified, as presented in Figures 1 and 2.

(2) Inventory analysis: it is truly difficult to collect data, thereby spending much time during the LCA study. For this reason, LCA supporting tools provide inventory. TOTAL also provides such the inventory datasets, referred from the Life Cycle Inventory (LCI) database [13]. This public database is useful because it assures completeness, representatives and consistency related to data quality. Table 4 presents a dataset used to record inventories on individual scenarios. Here, each vinyl packing contains 0.530 kg of Low Density Polyethylene Resin (LDPE) due to the calculation of 5.76E-04 m^2 of side wrapping with the density of 920 kg/m^3. In such a way, for example, the As-Is hot-season case consumes or emits 259 substantial inventories; meanwhile, the To-Be hot-season includes 190 inventories (due to the page limit, inventory sets are excluded).

(3) Impact assessment: commercial LCA tools including TOTAL provide an interface to select an appropriate impact assessment method such as Eco-indicator 99. A method

Table 4. The amount of LDPE and ton*km on individual scenarios

Inventory	As-Is off	As-Is hot	To-Be off	To-Be hot
LDPE (kg)	82.68	122.43	–	–
Diesel (ton*km)	13845	36996	13845	36996

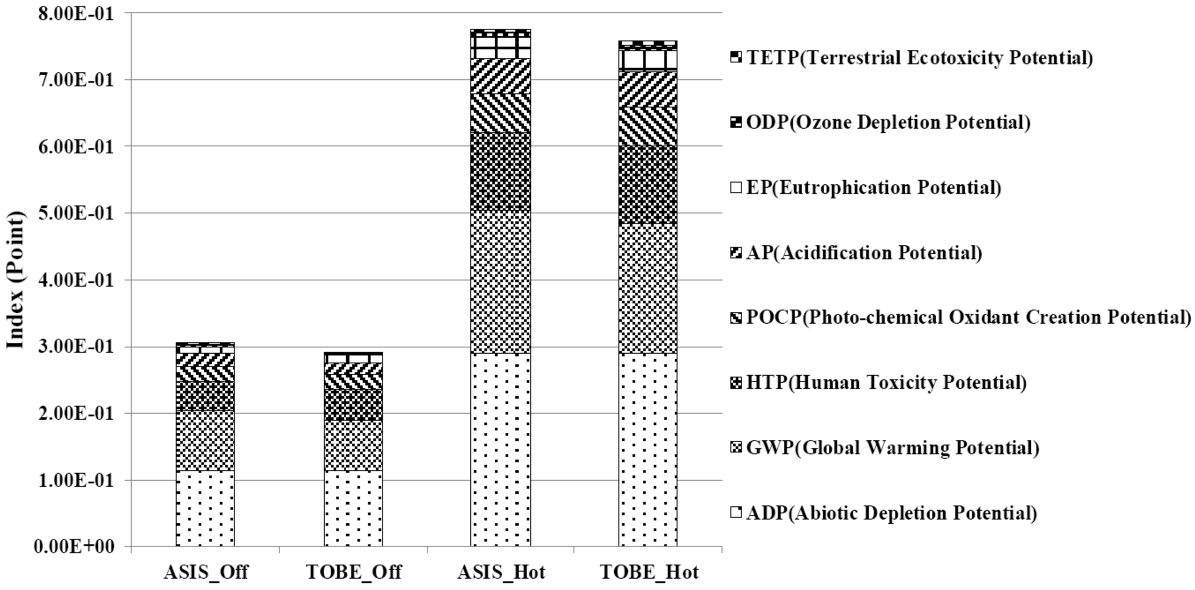


FIGURE 4. A stacked bar chart representing impact assessment results

issued by the Korean government is chosen for the impact assessment in this study. Figure 4 shows the resultant impact assessment indexes for the four scenarios. Abiotic Depletion Potential (ADP), Global Warming Potential (GWP) and Human Toxicity Potential (HTP) have been identified as the main influencing categories. The total index scored in the hot-season have average 254% higher than that of the off-season although the number of delivery units increases by an average of 148%.

(4) Interpretation: the results of the interpretation are identified as follows (sensitivity, consistency and completeness analysis are excluded due to the page limit).

- Environmentally-conscious transportation model: Figure 4 proves that To-Be model scores less environmental burdens, compared with As-Is model (4.3% in off-season; 2.6% in hot-season). The main reason comes from the exclusion of LDPE incineration. The elimination of LDPE incineration apparently elevates environmental friendliness in GWP and TETP categories although the portion is 19.4% of the most serious process, which corresponds to the transportation of a 5-ton truck to a recycling center B.
- Dynamics of environmental impact at a logistics center: The number of delivery units in the hot-season has increased to around one and a half time that of the off-season. On the other hand, the environmental impact index of the hot-season has increased by around two and a half times, which exceeds a proportional increment. The capacity of recycling center A is activated as a constraint; consequently, the transportation of residual delivery units to another recycling center results in severe environmental burdens. In an RL network, this dynamic constraint and result is a major differentiator, compared with the nature of the static product system.
- Major impact categories: The top impact categories are ADP, GWP and HTP in that order. Most of inventories are affected by operations of transportation vehicles. Diesel fuel consumption by vehicles is a dominant factor impacting the three categories.

5. **Conclusion.** It is certain that RL can support the re-circulation of consumed resources. However, RL is still in its infancy due to insufficient motivation and complexity of establishing RL networks. Against this background, the present work can contribute to proposing an environmentally-conscious transportation model and guiding an efficient

LCA application for RL-relevant models. The case study presents the environmental cause-effect analysis in a quantitative manner.

However, the boundary of the study was limited to a transportation model with relation to its transactions within a logistics center and recycling centers due to lack of data. Future research should extend the system boundary across not only the entire RL networks but also internal process chains inside recycling centers.

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