Proceedings of the 2015 Winter Simulation Conference
L. Yilmaz, W. K. V. Chan, I. Moon, T. M. K. Roeder, C. Macal, and M. D. Rossetti, eds.

A SIMULATION FRAMEWORK FOR THE COMPARISON OF REVERSE LOGISTIC NETWORK CONFIGURATIONS

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ABSTRACT

Reverse logistics networks are designed and implemented by companies to collect products at the end of their useful life from end users in order to remanufacture products or properly recycle materials. In this paper, we present a simulation framework for comparing alternative reverse logistic network configurations based on productivity and sustainability performance metrics. The resulting decision support tool enables the evaluation of user specified system and experimental parameters. An overview of the simulation framework is provided along with an example that illustrates the capabilities and functionality of the tool.

1 INTRODUCTION

Reverse logistics is most broadly defined as the “the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal” by Rogers and Tibben-Lembke (2002). Reverse logistics systems have gained attention in recent year due to increasing environmental concerns, opportunity for value recapturing, and legislations that require manufacturers to establish networks for product recovery at the end of their useful life (Gupta 2013). The baseline goal of establishing such networks is to transform industrial systems to involve the complete life cycle of the product (Dekker et al. 2004).

In this work, the comparison of the alternative configurations is performed on the basis of productivity and sustainability metrics. The trade-offs inherent in reverse logistics systems are identified and quantified, by considering various product, network, and operational characteristics. The trade-offs and their values depend on the specific scenario. The focus is given to complex products with high time sensitivity, since these products impose additional challenges and urgency with regards to reverse logistics system design. As an attempt to incorporate sustainability driven decisions, the trade-offs between economic and environmental metrics are considered. Alternative system configurations are formed by the choice of proposed alternative for each reverse logistics aspect, namely collection, sorting and testing, reprocessing. The simulation-based methodology is intended to act as a decision support tool for selecting the reverse logistics system configuration.

2 REVERSE LOGISTIC NETWORKS

Figure 1 shows the flow of main reverse logistics activities in a network. The location of individual activities and the number of facilities depend on the network structure. In this work, it is assumed that remanufacturing and recycling activities are performed in the same facility. Initially, returned products

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are collected at specialized collection centers; utilizing retailers for this purpose is a common practice. After the returned products are collected, they are sorted and tested to determine their next destination in the network. This process is usually referred to as product disposition (Blackburn et al. 2004; Sristava 2008), where the recovery alternatives can be listed as direct reuse, repair, remanufacture, recycle, or disposal. The selection of product disposition depends on numerous criteria, including the physical condition of the returned product and product age as a secondary criterion. To this end, product characteristics are defined that affect the choice of the disposition alternative (Guide et al. 2006).

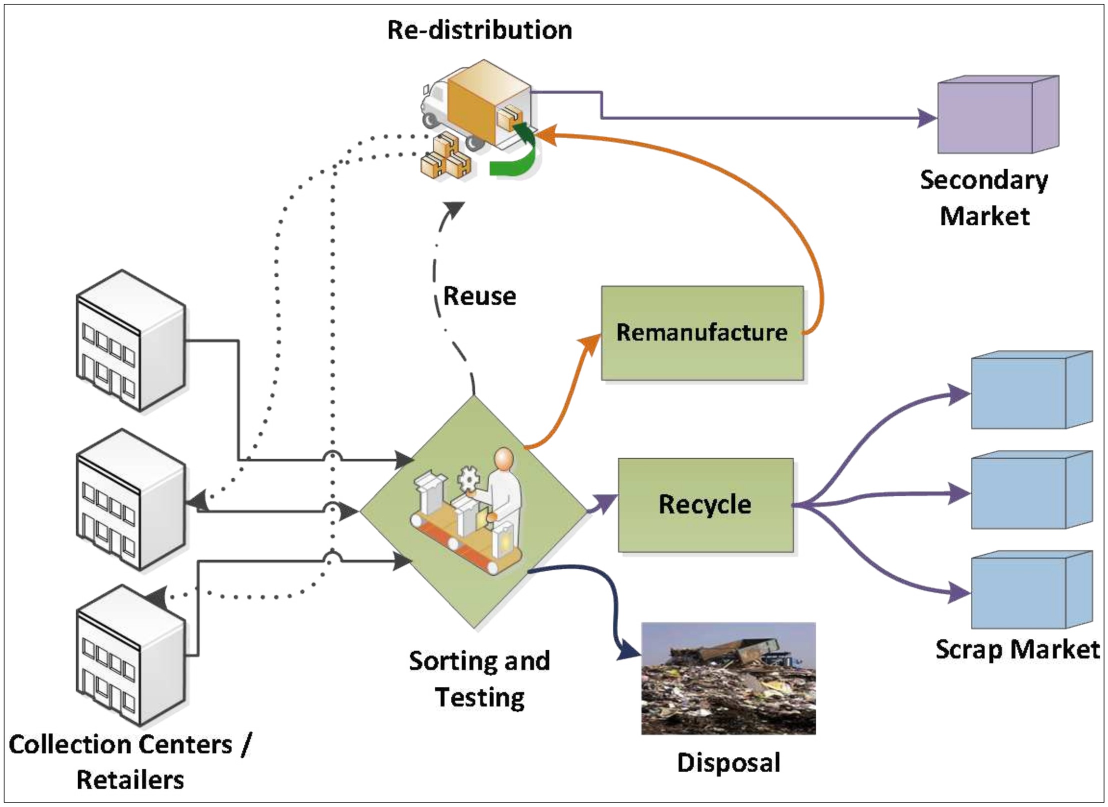


Figure 1: A reverse logistics network including collection, sorting, reprocessing, and redistribution.

Products that qualify for immediate reuse without the need for a major processing are transferred to a distribution center to be stored until there is demand at either primary or secondary market. If the product has lost its functionality, the recovery method is at the material level, which is referred to as recycling. Products that do not qualify for any of the recovery options are sent to a disposal location. Depending on the recovery method, the products or materials are sent to appropriate markets.

In addition to environmental benefits, establishing recovery networks is driven by direct and indirect economic opportunities. Reducing the dependency on virgin materials and disposal costs, and recapturing value by reselling the recovered product can be listed among direct benefits whereas companies also profit indirectly and acquire competitive advantage through building a green image (de Brito and Dekker 2003; Sharma and Singh 2013).

In some cases, companies are required to establish product take-back and recovery networks due to government regulations both in Europe and United States. Waste Electrical and Electronic Equipment (WEEE) directive and regulations in numerous U.S. states require producers to take back their end-of-life products, which is referred to as "producer's responsibility" (Walther and Spengler 2005). Government intervention may also be in the form of banning certain products from landfills and setting targets on recycling volumes. To this end, 20 states in U.S. have landfill bans on certain electronic devices (Electronic Recyclers). Companies can prevent future costs incurred by complying with regulations by taking pro-active action with regards to product recovery management (Thierry et al. 1995).

Even though driven by economic and environmental perspectives, designing reverse logistics systems is a challenging task, complicated by inherent sources of uncertainty in the quantity, quality, and timing of customer returns. The uncertainty in return rates is regarded as one of the most significant challenges in reverse logistics systems and has significant effects on scheduling of operational activities, forecasting return rates, and inventory management (Fleischmann et al. 2000; Gupta 2013). Incorporating uncertainty into decision making with regards to network design is important since changing the facility locations in the future is expensive (Listes and Dekker 2005). Another challenge is the complexity of the interactions between reverse logistics activities from collection to redistribution which complicates making strategic decisions with regards to reverse logistics systems. As a result, the decision making process must consider the trade-offs among productivity and sustainability metrics. One example to a strategic decision is the facility location problem where the prominent trade-offs are between capital costs, transportation and operating costs, and time in system. The existence of trade-offs and high level of complexity highlight the importance of multi-criteria analysis since the true performance of complex supply chains cannot be captured by a single-objective analysis (Beamon 1999).

Strategic decisions with regards to network design are dependent on product characteristics. These decisions, such as the number and location of facilities within the network define the configuration of the reverse logistics network. For instance, decentralized sorting might be more favorable for products that lose their economic value rapidly, which can be referred to as time sensitivity or economic obsolescence. The selection of the recovery method is also based on factors such as economic value and obsolescence of the product in addition to its physical condition.

Several models have been published concerning reverse logistics network design with deterministic parameters including Jayaraman et al. (1999), Lu and Bostel (2007), Cruz-Rivera and Ertel (2009). However, most of these models are limited in addressing the location decision of certain facilities within the network, and adopt a static approach to a problem where the effect of uncertainty is dynamic on the network performance along with other parameters. Uncertainty is incorporated into network design models in order to make robust location decisions through various approaches such as parametric analysis, stochastic programming, and queuing models (Listes and Dekker 2005; Barker 2010). Some authors also performed qualitative analysis on network types, depending on product characteristics (Fleischmann et al. 2000). Hence; there is still need for a generic tool that can evaluate and compare the trade-offs across alternative reverse logistics system configurations in terms of multiple criteria, considering the effect of uncertainty over time. Our methodology identifies various product characteristics indicative of the reverse logistics system configuration, which are obtained by looking at commonly addressed system inputs in case studies.

3 SIMULATION MODELING AND ANALYSIS FRAMEWORK

The simulation-based methodology aims to compare alternative reverse logistics network configurations under uncertainty. The network configurations are evaluated in terms of productivity and sustainability metrics and the trade-offs inherent in reverse logistics network design are quantified. A discrete-event simulation model serves as the basis for a customizable experimental framework that is utilized to evaluate alternative network configurations. Figure 2 displays a diagram of the modeling and analysis framework for the simulation-based decision support tool.

The tool is designed around a flexible simulation core that simulates the operation of the reverse logistics network and computes relevant system performance measures including both productivity and sustainability measures. Input to the analysis tool includes (a) parameters of the reverse logistics network configurations (alternative facility locations, transportation modes, etc.); (b) product characteristic and disposition parameters; and (c) experimental design parameters. The output of the analysis tool includes system performance measures resulting from the experiments performed on specified network configurations. The components of the simulation-based tool are detailed in the following sections.

Figure 1: Modeling and analysis framework for reverse logistics network decision support tool.

3.1 Simulation Model Structure

The central discrete event simulation model is designed to represent the general structure of reverse logistics networks and their dynamic behavior. Figure 3 depicts the general network structure which includes product returns to collection centers, transportation to sorting centers where product disposition is determined, transportation to processing centers for remanufacturing or recycling, and distribution or disposal. The general model is constructed to be flexible to allow for the representation of a wide array of system configurations including alternatives for transportation systems, separate or co-located sorting and processing functions, processing capacities, product return distributions, and disposition distributions.

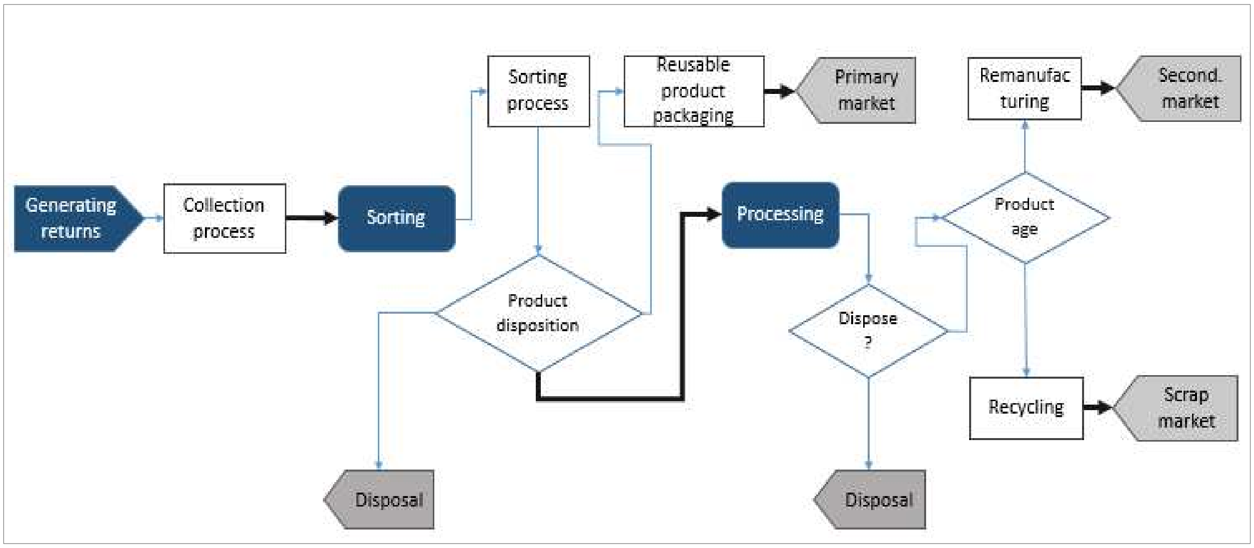


Figure 3: Main activities and process flows in the simulation model.

The simulation time is driven by events such as arrival of entities (returned products) to the system, completion of processing at various locations in the network (collection, sorting, reprocessing), and reaching the shipping size to be transferred to another location. Returns are generated according to a truncated normal distribution, where the range lies within $[0, \infty)$. Processing times are exponentially distributed, where a constant simultaneous processing capacity is defined by the user. Randomness is also introduced in the transportation operation, by sampling the vehicle speed from a uniform distribution at each shipment.

The flow of activities that take place in the model are shown by the directed arcs in Figure 3. The thicker arcs in Figure 3 represent physical transportation and the fact that there is an accumulation process before the shipment. For instance, after the collection process, products are accumulated up to a specified shipping size and then shipped to the sorting facility. There are two additional disposition decisions that take place in the processing center. If the products that are incorrectly classified as remanufacturable in the sorting center, they are disposed of based on a user-specified probability. If a product is beyond the remanufacturing age threshold, the product is sent to the recycling process.

3.2 Configuration Models

Configuration models are the set of reverse logistic network alternatives and associated parameters that the user would like to evaluate and compare system performance. The configurable system components include collection, sorting, and processing (remanufacturing and recycling), as follows:

- ***Collection:***
    - The number and location collection centers to which products are returned.
    - The assignment of collection center to sorting center (closest, designated, etc.)
- ***Sorting:***
    - The number and location of sorting centers
    - The assignment of sorting centers to processing centers and disposal locations.
- ***Processing:***
    - The number and location of specialized processing centers where recovery of the product is performed. Processing centers are divided into remanufacturing and recycling centers.
    - The assignment of distribution and disposal locations.

Along with configuration alternatives, operational parameters that will remain fixed across the various configurations are also specified here including processing capacities, shipping sizes, and daily operational hours.

3.3 Product Characteristics and System Specifications

Product characteristics and system parameters are specified by the user to define the reverse logistics system functions and activities. These parameters include the following:

- ***Fixed and variable costs:*** Fixed costs include the facility opening and truck acquisition costs. Transportation, operating, and inventory holding costs are identified as the variable cost parameters.
- ***Transportation parameters:*** Vehicle capacities and speeds.
- ***Processing parameters:*** Processing times, number of resources, processing batch size.
- ***Distribution of product returns:*** Probability distribution describing the mean and variability of the daily product returns at the collection centers.
- ***Distribution of the returned product condition, age, and disposition:*** Distribution describing the likelihood that a returned product will fall into user-defined condition and/or age categories. Given the condition and age category, the user defines the likelihood of the product disposition of re-use, remanufacture, recycle, or disposal.

3.4 User Defined Experimentation for Alternative Selection

This component constitutes the experimental framework to evaluate and compare scenarios based the user defined alternative set of configuration models under various experimental conditions. The following steps are used in designing the simulation experiments:

- Identifying the experimental factors from a list of potential factors and their levels;
- Identifying the responses (performance metrics); and
- Identifying the factor combinations (scenarios).

Once the alternative scenarios have been identified, the user can specify the number of replications of each scenario to run.

3.5 System Performance Metrics

The output of the simulation tool is the comparison of performance metrics defined. The metrics, which involve both productivity and sustainability metrics, are listed in Table 1.

Table 1: Productivity and sustainability metrics used in the comparison of alternative systems.

Productivity and Sustainability Metrics	
Transportation cost	Cost of transporting items within the reverse logistics network
Collection, sorting, and processing cost	Variable cost incurred by reverse logistics activities such as collection, sorting, remanufacturing, and recycling
Inventory (WIP) cost	Time weighted average of the work-in-process holding cost of products at each facility within the network
Disposal cost	Costs incurred in disposing the returned products that do not qualify for any of the treatment options
Fixed opening cost	Fixed cost associated with each facility within the network
Time in system	Recorded for each product disposition category from the time of collection to final disposition
Value of recovery	Revenue earned from recovering products
Emissions	CO_2, CH_4, N_2O emissions due to transportation activities

3.6 Comparison and Ranking of the Network Configurations

The comparison of the configurations is based on performance metrics that are categorized under fixed and variable costs, time in system (i.e., responsiveness of the network), and emissions. When the performance metrics have different units, one way of comparing alternative scenarios is to convert every metric to monetary terms and calculate a single score for each alternative. However, metrics such as time in system and emissions may not be straightforwardly converted to cost. Instead, a weighted sum approach is employed in order to form single scores. Each metric is assigned an importance weight factor and the weighted metrics are summed. Metrics that have the same unit are assigned equal weight factors. The selection of the configuration can also depend on the user defined performance metrics. For instance, if a user is interested in a ranking based only on the time in system for remanufactured products, the output of the tool will be the indication of the network configuration that leads to the shortest time in system.

3.7 Implementation

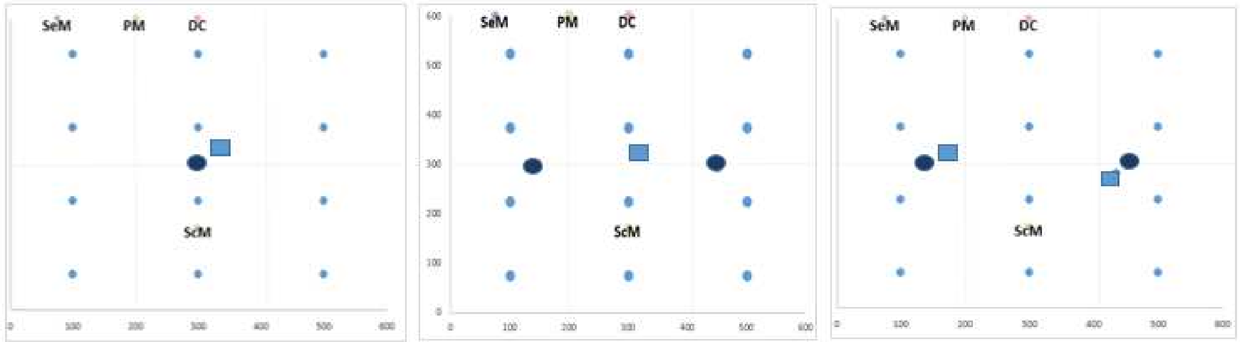
The simulation-based reverse logistics network comparison tool is implemented in Simio with a MSExcel user interface that is used for specifying the system and network configuration parameters. In addition, the output performance measures resulting from the simulation model are written to MSExcel. As such, the user is not required to have expertise in simulation modeling in order to use the tool and can focus their efforts on the comparisons and experiments required for decision making.

4 EXAMPLE COMPARISON OF REVERSE LOGISTICS NETWORK CONFIGURATIONS

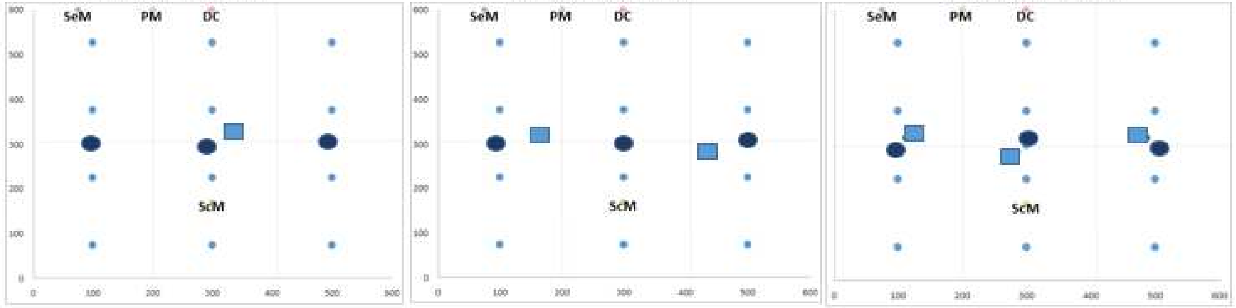
In this example, we compare six alternative reverse logistics network configurations to illustrate the use of the simulation-based tool. The reverse logistics system consists of a single product type that is returned to 12 collection centers within a 600 x 600 km region. The configurations scenarios are summarized in Table 2 and illustrated in Figure 4. The scenarios contain 1-3 sorting locations and 1-3 processing centers.

Table 2: Scenarios considered in the reverse logistics example.

	Abbreviation	Collection Locations	Sorting Centers	Processing Centers
Scenario 1	1S1P	12	1	1
Scenario 2	2S1P	12	2	1
Scenario 3	3S1P	12	2	2
Scenario 4	2S2P	12	3	1
Scenario 5	3S2P	12	3	2
Scenario 6	3S3P	12	3	3



Scenario 1 (1S 1P) Scenario 2 (2S 1P) Scenario 3 (2S 2P)



Scenario 4 (3S 1P) Scenario 5 (3S 2P) Scenario 6 (3S 3P)

Figure 4: Scenarios 1-6: reverse logistics network configurations - ●: sorting centers, ■: processing centers; PM: primary market; SeM: secondary market; ScM: scrap market; DC: distribution center.

Product returns are made at the 12 collection centers. The daily returns at each collection center are generated at the start of each day and follow a truncated normal distribution. The aggregate return rage is 144 items per day with a standard deviation equal to 50% of the mean. Each returned product is assigned a condition category and disposition based on the probability distribution displayed in Table 3. Products accumulate at the collection center until the shipping size of 120 items is reached. Then the items are transported to the assigned sorting center.

Travel time variation is modeled by sampling a vehicle speed. In this example, the speed for each trip has a uniform distribution with a minimum of 40 and a maximum of 50 km/hr. Also, the distance between locations are calculated as linear distances between locations.

After arriving at the sorting center, products are dispositioned. Products with a disposition of reuse are sent to the distribution center. Products designated as remanufacture or recycle are sent to the processing center. The products accumulate until the shipping size is reached. The processing parameters of each the sorting, remanufacturing, and recycling functions are shown in Table 4.

Table 3: Distribution of product condition and disposition.

Product Condition	Probability	Product Disposition			
		Reuse	**Remanufacture**	**Recycle**	**Disposal**
1	0.60	0.75	0.20	0.05	0.00
2	0.25	0.30	0.50	0.15	0.05
3	0.15	0.05	0.30	0.50	0.15

Table 4: Processing parameters.

	Collection	Sorting	Recycling	Remanufacturing
Processing Capacity	20	12	27	21
Mean of the Handling/Processing Time Distribution(hr)	0.1	0.6	6.5	10
Daily Output Potential	2400	240	49	25

The simulation model was run under each of the 6 alternative scenarios. The simulation was run for 180 shifts and replicated 10 times, with 30 shifts of warm-up period. Since the operation lasts for 12 hours in a day and it is assumed that a new shift continues from where the previous one left off. Performance measures were collected for each scenario. The mean and standard deviation of each measure across the 10 replication is shown in Table 5.

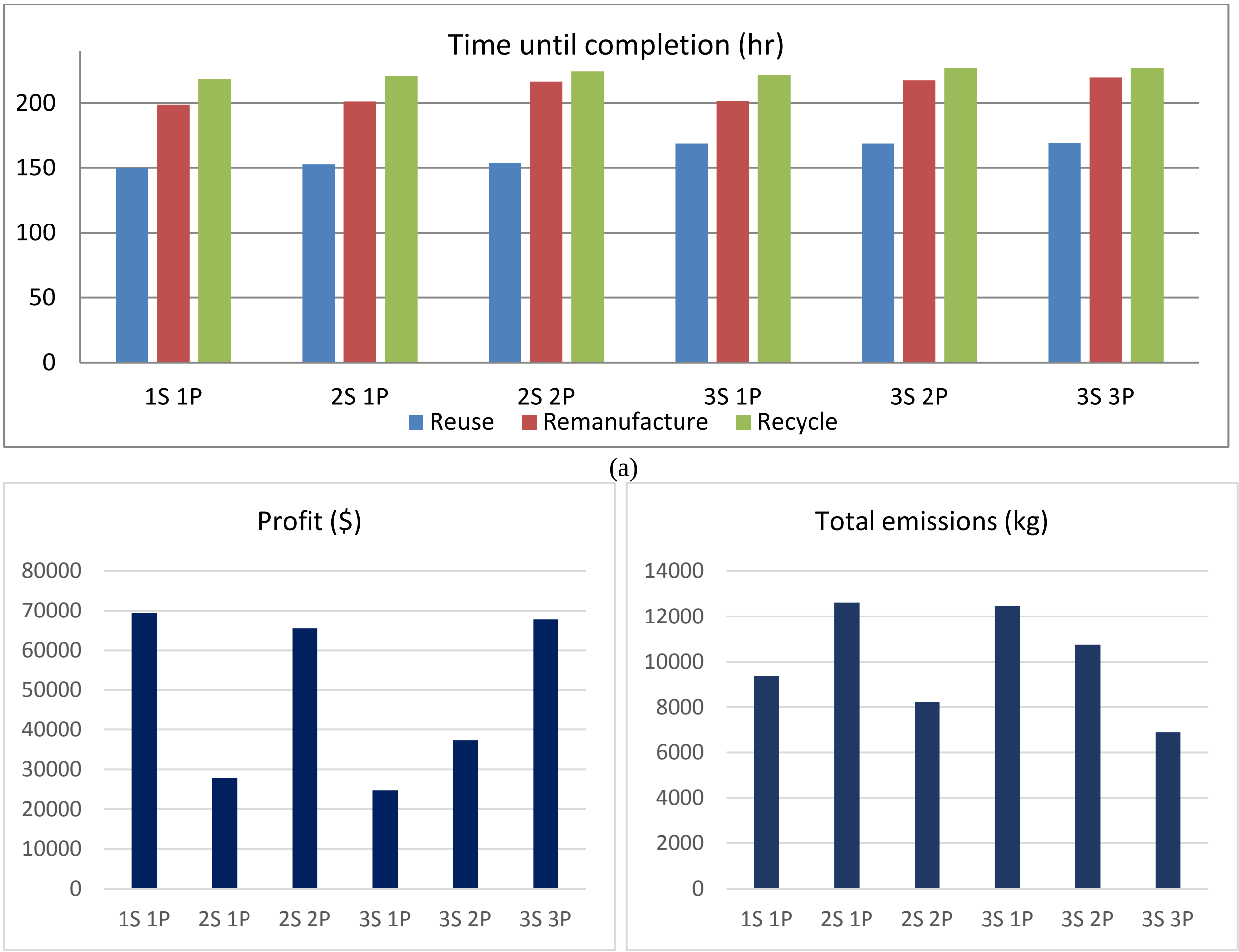
Figure 5(a) shows the time in system comparison for reuse, remanufactured, and recycled products, for each scenario. Although there are some small differences among the time to completion for the various disposition categories over the six scenarios, there does not appear to be a particular scenario that dominates the others in terms of completion time.

Figure 5(b) represents the comparison of expected profit for each scenario. In general, scenarios with single processing center and decentralized sorting centers (2S 1P, 3S 1P) perform poorly due to high transportation costs incurred from long travel distances between sorting and processing centers. Total costs of 1S 1P and 3S 3P configurations are very similar, however, the contributing cost components exhibits differences. For instance, the transportation cost dominates the total cost of the first scenario, while the dominating cost component in the latter case (3S 3P) is the fixed opening costs.

Finally, emissions are compared in Figure 5(c), Since all type of emissions represent same relative behavior, only CO 2 emissions are depicted above. The last scenario (3S 3P) leads to lowest emissions, due to decreased distances and shipping sizes between collection and sorting centers, as well as sorting and processing centers.

Table 5: Simulation results for each of 6 scenarios – Mean and (Std. Dev.)

		1S 1P	**2S 1P**	**2S 2P**	**3S 1P**	**3S 2P**	**3S 3P**
Time until completion (hr)	Reuse	149.65 (1.44)	152.99 (1.58)	153.95 (1.45)	168.78 (1.64)	168.73 (2.36)	169.34 (2.45)
	Remanufactured	198.83 (2.64)	201.34 (1.40)	216.37 (2.56)	201.66 (1.34)	217.35 (1.63)	219.7 (3.36)
	Recycled	218.70 (2.80)	220.60 (1.66)	224.33 (3.29)	221.39 (1.96)	226.65 (2.83)	226.76 (7.83)
	Transportation cost ($1.5/km)	86,216 (722)	120,140 (1,465)	76,332 (768)	121,851 (707)	104,213 (1283)	64,485 (464)
Processing Cost ($)	Sorting ($1.5/p)	36,244 (378)	36,182 (587)	35,917 (318)	36,142 (494)	36,247 (569)	36,044 (379)
	Remanufacturing ($6/p)	40,383 (738)	40,268 (737)	39,722 (449)	40,113 (747)	40,395 (700)	39,910 (647)
	Recycling ($8/p)	28,506 (543)	28,632 (569)	28,162 (437)	28,722 (325)	28,757 (447)	28,716 (295)
Fixed opening costs ($)	Sorting & Processing	85,200	91,800	96,000	93,000	97,200	104,400
Inventory cost ($)	Sorting	4,528 (155)	5,379 (81)	5,361 (111)	6,168 (90)	6,209 (111)	6,124 (86)
	Processing	17,684 (428)	17,408 (414)	17,771 (363)	17,087 (581)	17,741 (314)	18,008 (318)
Value ($)	Reuse ($20/p)	257,174 (2,920)	256,764 (4,474)	255,604 (2,766)	256,864 (4,105)	256,824 (4,709)	255,102 (3,109)
	Remanufacture ($14/p)	75,422 (1,475)	75,103 (1,574)	73,993 (1,134)	75,006 (1,383)	75,303 (1,412)	74,451 (967)
	Recycle ($10/p)	35,633 (679)	35,790 (712)	35,203 (547)	35,902 (406)	35,946 (559)	35,895 (369)
Emissions	CO2 (kg)	9,356 (104)	12,612 (204)	8,217 (111)	12,473 (97)	10,754 (176)	6,877 (67)
	CH4 (g)	110 (1.27)	150 (2.48)	100 (1.34)	150 (1.18)	130 (2.14)	80 (0.81)
	N2O (g)	70 (0.78)	90 (1.52)	60 (0.82)	90 (0.72)	80 (1.31)	50 (0.50)



(a)

(b) (c)

Figure 5: Comparison of the simulation results for each of the six scenarios – (a) Time Until Completion; (b) Profit; and (c) Total Emissions.

To compare the scenarios the weighted factor comparison displayed in Table 6 is used to calculate a weighted score from the performance measures. For this example, time to completion is assigned a weight of 0.1, expected costs and revenues are given a weight of 0.5, and expected emissions are given a weight of 0.4. The weighted factor comparison is shown in Table 6. For this reverse logistics network, the configuration resulting in the best weighted score is scenario 3S 3P which has 3 sorting centers and 3 processing centers.

Table 6: Weighted factor comparison of the six alternative scenarios.

	Weight	**1S 1P**	**2S 1P**	**2S 2P**	**3S 1P**	**3S 2P**	**3S 3P**
Weighted TIS	0.1	-57	-57	-59	-59	-61	-62
Weighted Cost	0.5	-149,381	-169,905	-149,633	-171,541	-165,381	-148,843
Weighted Value		184,115	183,829	182,400	183,886	184,037	182,724
Weighted Emissions	0.4	-3,814	-5,141	-3,351	-5,085	-4,386	-2,803
Score		30,863	8,726	29,357	7,201	14,209	**31,017**

5 CONCLUSIONS AND FUTURE WORK

In this paper, we have overview of a simulation-based analysis tool that can be used for the evaluation and comparison of alternative configurations for reverse logistics networks. The tool considers both productivity and sustainability performance measures and provides a method for conducting a weighted factor comparison for evaluating configuration alternatives.

The next steps in our research will involve an extensive experimental performance evaluation to determine the factors most influential in determining system performance. In addition, we plan to investigate the inclusion of other productivity and sustainability performance measures that could influence the decision making process.

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