Design of Supply Chain Damage Recovery Systems

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The growth and development in the field of manufacturing has led to long supply chains, which have raised the need for preventing damage during transportation. During each stage of the supply chain, the yield is different because of disruptions during transit, which may lead to a random yield at the retailer. Decision-makers strive to implement strategies that enable the supply chain to quickly return to the steady state, while minimizing the significant costs associated with recovery of the disruption. This paper focuses on the recovery of products that are damaged during transit. Recovery models have been developed by considering different types of damage. A methodology for determining a cost-effective recovery model has been developed to ensure maximum profit and meet customer demand. Three case studies are used to validate the proposed methodology. Results specify that specific options for recovering the damaged product can lead to significantly different expected profits.

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I. INTRODUCTION

Supply chains have raised the need for preventing damage during shipping and transportation. With poor packaging, products may get damaged during transit. The types of packaging and method of shipping influence the amount and type of damage. Good product packaging helps to ensure that customers receive the product without any damage. The most common hazards during transportation include shocks, vibrations, accidents, and mishandling. For example, during the transportation of products in trucks, shocks might occur when the condition of the road is poor. Damage from accidents and mishandling issues are not completely within the control of packaging. However, the impact of these can be minimized by proper packaging.

Supply chain disruptions are expensive, and appropriate actions to decrease negative effects to the supply chain system must be taken into account to ensure smooth performance of the system. When disruptions occur, strategies that will enable the supply chain to quickly return to the steady state while minimizing significant costs associated with recovery of the disruption must be developed.

Disruptions and damages can occur at all stages of the supply chain. For instance, disruption may occur during production at the factory or during shipping when there are unusually long delays at ports. The type of disruption and damage is different at each stage. As a result, the percentage of damaged goods during each stage is also different. Thus, the yield at the final stage is dependent on the damage that occurs at each stage. The damage caused during transit may be categorized into three levels: minor damage, repairable, and severe. At the minor damage level, the product has physical damage but there is no loss to its functionality, i.e., the product may have scratches and dents but is still functional. In the case of repairable damage, the product has physical damage that affects its required functionality; however, the product can be repaired by replacing some of its parts. In the case of severe damage, the product has physical damage and the damage is severe enough that a repair option is not feasible; however, the product can be salvaged as parts from the damaged product, the parts could be reused, and some cost can be recovered.

Depending on the level of the damage to the product, a decision must be made to determine the appropriate level of recovery for the damaged products. In a forward supply chain, damaged products can be recovered in different ways based on the type of damage. When the product is damaged but not enough to affect its functionality, the product can be sold with scratches and dents or shipped back to the recovery center for repair. If the damaged product has functional damage and the repair option is not possible, then two options are available: first, the products are rejected and send to a recovery center to be disassembled and sold as parts; or the products are rejected and shipped back to the home factory. This paper proposes a comprehensive approach that considers all types of damage that may occur during transit and recommends models and methods to maximize profit and meet customer demand.

II. LITERATURE REVIEW

According to Shear et al. (2002), the value of products that are returned each year is around $100 billion. Guide Jr. et al. (2006) and Shear et al. (2002) identified the following reasons for returning products - customer dissatisfaction, product evaluation, shipping damage, defective merchandise, end of lease, and end of life. Thierry et al. (1995) described five recovery options: repair, refurbishing, remanufacturing, cannibalization, and recycling. They focused on remanufacturing and refurbishing the product to restore it to an "as-good-as-new" condition by changing components or reusing used parts. The quantity, quality, and time of product return are usually difficult to forecast and will increase uncertainty along with demand risks in recovery systems. Although all of the above papers considered the reasons for products to be returned, they did not identify procedures for determining the cost contributions of the damage during shipping to the supply chain system.

The management of the return of products has been studied by different authors. Fleischmann et al. (1997) reviewed quantitative models for reverse logistics in three operational areas (distribution planning, inventory control, and production planning). Francas and Minner (2009) studied the network design problem when a company manufactures new products and remanufactures returned products in the same facilities, and they examined the performance and capacity for the manufacture of these products when demand and returned products are uncertain. Fleischmann et al. (2000)

classified the general characteristics of recovery networks into three categories (product characteristics, supply chain characteristics, and resource characteristics). With respect to profitability of the remanufacturing option, it is assumed that refurbishing damaged or used products costs less than producing new products (Aras et al., 2006). These papers primarily addressed issues related to capacity for manufacturing and did not address the issue of the costs that are incurred due to damages that occur during shipping.

Guo and Jiang (2006) developed a decision model to recycle electronic products by considering three levels of recycling (product reuse, part reuse, and material reuse). Jorjani et al. (2004) developed a piecewise linear concave program to decide the optimal allocation of disassembled parts to five disposal options (refurbish, resell, reuse, recycle, and landfill) in order to maximize the overall return. Tan and Kumar (2008) used a linear programing model to evaluate three end-of-life options for each part (repair, repackage, or scrap). All of these papers dealt with recycling, and implicitly considered the cost of repair, repackaging, or scraping products.

Hishamuddin et al. (2013) developed a recovery model for a two-stage production and inventory system under transportation disruption and developed a heuristic model to obtain the transportation costs in the supply chain system. The research addressed issues related to building a network to prevent disruptions in the supply chain when events such as tsunami, or earthquake may occur. Azad and Davoudpour (2010) considered facilities with random disruption risk to design a reliable supply chain network. They used tabu search and simulated annealing algorithms to solve the models. Similarly, Aryanezhad et al. (2012) designed a supply chain network considering unreliable supplier and distribution centers. They found that the quantity of products delivered may decrease due to unreliable distribution centers. They formulated the problem as a nonlinear integer programing to minimize total cost and used Lagrangian relaxation and genetic algorithms to solve it. They determined optimal distributions center locations and the subset of customers to be served, assigned customers to distribution center, and determined the order quantity. Qi et al. (2010) used the concept of disruptions to develop an integrated supply chain network that can be used when suppliers and retailers are unreliable. This nonlinear integer programming model minimizes the total annual cost, including fixed cost, inventory cost, transportation cost, and lost sales cost. Moreover, they integrated the model to decrease disruptions to retailers by determining the number of retailers that should be opened, their locations, and frequency and order size for each retailer.

Although there have been several works that dealt with reverse supply chains and disruption, there has been no significant literature that looks at the design of supply chains when damages occur during shipping. In the design of supply chains systems, it is important to identify the cost of damages that occur during shipping, which in turn influences the cost of the supply chain system. This research has developed a comprehensive set of recovery models which will lead to the selection of the least cost option with the highest yield in the supply chain. The use of these recovery models is demonstrated using case studies.

III. DAMAGE RECOVERY APPROACH

Notations:

A_{ij} Distance from node "*i*" to node "*j*"

B_{ij} Cost per mile from node "*i*" to node "*j*"

d_n Quantity shipped for product "*n*"

$D_{n,i}$ Disassembly cost for product "*n*" at node "*i*"

E Unit cost

F_n Lost cost for product "*n*"

I_{i+1} Inspection cost at stage "S_{i+1}"

O_{zn} Repackaging cost using type "z" packaging for product "*n*"

$P_{Z,n}$ Packaging cost using type "z" packaging for product "*n*" at the first stage

q_{i+1} Quantity of good units received at node "S_{i+1}"

$T_{v,n}$ Repair cost for type "*v*" damages for product "*n*"

U Total shipping cost for the supply chain

U_{ij} Shipping cost from node "*i*" to node "*j*"

W_n Cost of product "*n*"

X_{vnij} Percentage of type "v" damages for product "*n*" when shipping from node "*i*" to node "*j*"

$\Omega_{3,n}$ Sales price for type 3 damages for product "*n*"

The forward supply chain can be improved by reducing the cost associated with products damaged during shipping. Products damaged during shipping leads to customer dissatisfaction, loss in profits, and increased overhead costs. Depending on the product price, damage level, and lead time, companies may adopt strategies to recover products damaged during shipping. The objective of this research is to develop models for analyzing the damaged-product recovery process for various types of products. The damages that occur during shipping have been classified into three different types. Type 1 defects are those with no functional damage but may have cosmetic damage. These could be sold in the secondary market at reduced prices. Type 2 defects have some functional damage as well. However, these products may be repaired and restored to full function. Type 3 defects result in products that cannot be recovered to functional condition. Products with Type 3 defects are typically dismantled and often sold as parts.

Five recovery models have been developed. The first model deals with a supply chain network in which no recovery is being done. This can be applied to cases in which the recovery costs are very high or the product costs are low enough that the product recovery is not profitable. Products such as kitchen utensils are good examples of this type of product. The second model is used when the recovery of products with Type 1 and Type 2 damages are performed, while products with type 3 damage are disassembled and sold as parts. This type of recovery model is used when the product retains its value and is functional with Type 1 & Type 2 damages. Automobiles are a prime example of this type of products. If these products have Type 3 damages, the product can be sold as parts. In the third model, products with all types of damages are collected and shipped back to the manufacturer for recovery. These type of products are either too valuable or may have proprietary information. Hence, it is not advisable for products of this type to be repaired in third party facilities. In the fourth model, the recovery of products with Type 1 and Type 2 damages are performed, while products with Type 3 damage are rejected. This model can be applied to products that are still functional and retain its value with Type 1 and Type 2. However, with severe damage, these products do not have any value and hence are rejected/scrapped. Products such as clothes are good candidates for this model. And finally in the fifth model, products with type 1 damage are sent to a local recovery center, products with type 2 damage are shipped back to the manufacturer, and products with type 3 damage are rejected after inspection. This model can be used when products have proprietary information that may not be revealed when fixing Type 1 damages. However, Type 2 damages may compromise this information or the product repair is too complex to be done by a third party or may need expensive tooling that cannot be duplicated. Type 3 damages for this type of product is too expensive to fix and hence the product may be scrapped. These models have been developed to provide a methodology for supply chain designers to calculate costs for various situations that may occur in the design of supply chains. In addition, as demonstrated in case studies, the best location of the inspection points based on the percentage of damages during shipping can be determined using these models.

3.1. Recovery Model 1

Recovery Model 1 considers a system consisting of two nodes (S_i and S_{i+1}) and one route. Products that are shipped from node S_i reach node S_{i+1} and can be inspected for damage at that node. The damaged products are identified and separated. There is no recovery of damaged products. The objective of this model is to obtain the cost per unit and quantity of good products received at the final destination. Figure 1 shows the system for Recovery Model 1. This type of model is used when the product costs are low and the repair and recovery costs are relatively high. This type of model may also be used when the product costs are high, but the recovery and repair costs are difficult and expensive.

3.1.1. Mathematical Representation for Recovery Model 1

This subsection shows the calculations needed for Recovery Model 1 in order to determine the total cost and quantity of good units delivered. The total shipping cost (U) (Equation 1) from node $S_{(i)}$ to node $S_{(i+1)}$ is the product of the following: quantity of products shipped, distance from node $S_{(i)}$ to node $S_{(i+1)}$, cost per mile, and packaging cost. In this the packaging cost is added only for node S_0.

$$U_{ij} = d_n(\mathrm{A}_{ij} B_{ij} + P_{Z,\mathrm{n}} + I_{i+1}) \tag{1}$$

The total quantity that arrives in good condition at node $S_{(i+1)}$ is given by Equation 2.

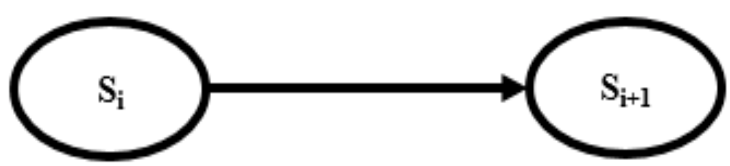

FIGURE 1. RECOVERY MODEL 1.

$$q_{i+1} = d_n \left(1 - \sum_{v=1}^{3} X_{vni(i+1)} \right) \tag{2}$$

After obtaining the total shipping cost, and total quantity arriving at node $S_{(i+1)}$, the cost per unit can be obtained by

$$E = (U_{ij} + d_n W_n) / q_{i+1} \tag{3}$$

3.1.2. Numerical Example 1 for Recovery Model 1

This numerical example illustrates the steps necessary to calculate the unit cost and quantity received at the $S_{(i+1)}$ node of this model. The parameters for example 1 are shown in Table 1.

3.2. Recovery Model 2

In this model, consider the system shown in Figure 2, which consists of two nodes and one recovery center. Here, there is damage during shipping between two nodes, and products are inspected at node $S_{(i+1)}$. The damaged products are separated and shipped to the recovery center for repair. At the recovery center, types 1 and 2 damaged products are recovered, and type 3 damaged products are disassembled and sold as parts. The recovered products are shipped back to node $S_{(i+1)}$. This model is used when product costs are high. In addition, the parts have significant value when recovered. The repair or recovery costs are relatively low when compared to the cost of the parts or the product.

TABLE 1. PARAMETERS OF EXAMPLE FOR RECOVERY MODEL 1.

Parameter	Value	Parameter	Value
A_{ij} (mile)	500	W_n ($)	30
B_{ij} ($)	0.03	$P_{z,n}$ ($)	2
X_{vnij} (%)	11	d_n (unit)	100
I_{i+1}($)	2		

Shipping cost from node $S_{(i)}$ to node $S_{(i+1)}$: $U_{ij} = 100(500 * 0.03 + 2 + 2) = \$1,900$

The number of good products received at node $S_{(i+1)}$: $q_{i+1} = 100\left(1 - 0.11\right) = 89$

Cost per unit: $E = (1,900 + 3,000) / 89 = \$55$

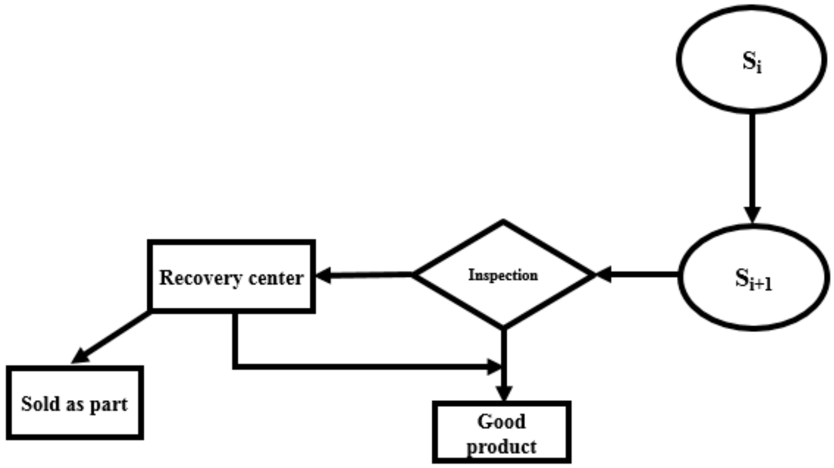

FIGURE 2. RECOVERY MODEL 2.

3.2.1. Mathematical Representation for Recovery Model 2

The shipping cost (U) from node $S_{(i)}$ to node $S_{(i+1)}$ can be obtained by using equation (1). The shipping cost for damaged products from node $S_{(i+1)}$ to the recovery center is

$$U_{i+1,r} = B_{ij} * A_{ij} * d_n \sum_{v=1}^{3} X_{vnij} \quad (4)$$

The shipping cost for the repaired products from the recovery center to $S_{(i+1)}$ is

$$U_{r,i+1} = B_{ij} * A_{ij} * d_n (\sum_{v=1}^{2} X_{vnij}) \quad (5)$$

The total shipping cost is the sum of equations (1), (4), and (5):

$$U = U_{ij} + U_{i+1,r} + U_{r,i+1} \quad (6)$$

The damaged products at $S_{(i+1)}$ are identified and separated, and the damaged products are shipped to the recovery center for repair. After sorting all types of damage at the recovery center, all costs associated with damaged products can be calculated to determine the total recovery cost (TRC). The repair cost associated with the recovery of type 1 damaged products is

$$T_{v,n} = d_n (X_{1nij} T_{1,n}) \quad (7)$$

The repair cost associated with the recovery of type 2 damaged products is

$$T_{v,n} = d_n (X_{2nij} T_{2,n}) \quad (8)$$

The cost associated with the disassembly cost is

$$D_{n,i} = d_n (X_{3nij} D_n) \quad (9)$$

The repackaging cost at the recovery center is

$$O_{Z,\mathrm{n}} = d_n(\sum_{v=1}^{2} X_{vnij}) * O_{Z,\mathrm{n}} \tag{10}$$

The total recovery cost is the sum of costs in Equations 7 through 10.

$$TRC = d_n[[(\sum_{v=1}^{2} X_{\mathrm{vnij}} T_{\mathrm{v,n}}) + ((\sum_{v=1}^{2} X_{vnij}) * O_{Z,\mathrm{n}})] + (\mathrm{X}_{3nij}\ D_n)] \tag{11}$$

The total quantity that arrived in good condition at node $S_{(i+1)}$, including recovered products is

$$q_{i+1} = d_n\left[\left(1 - X_{3nij}\right)\right] \tag{12}$$

The sale price for type 3 damages is

$$\Omega_3 = d_n X_{3nij} * \Omega_{3,n} \tag{13}$$

The cost per unit at node (i+1), which is the ratio of the total shipping cost, total recovery cost, product cost, minus the sales price for type 3 damages to the number of good units arriving at node (i+1), is

$$E = [(U_{ij} + U_{i+1,r} + U_{r,i+1}) + TRC + d_n W_n - (d_n X_{3nij} * \Omega_{3,n})] / q_{i+1} \tag{14}$$

3.2.2. Example for Recovery Model 2

This example illustrates steps for calculating the unit cost and quantity received at the last node of Recovery Model 2. The parameters for numerical example 2 are shown in Table 2.

3.3. Recovery Model 3

In this model, consider the system shown in Figure 3, which consists of two nodes. Here there is damage during shipping between the two nodes, and the products are inspected at node $S_{(i+1)}$. The damaged products are separated and shipped to the recovery center at the main stage (S_0) for repairs. At the recovery center, products with all types of damages are recovered and then shipped back to node $S_{(i+1)}$. This model is used when the products are expensive. This type of recovery model is used when either the expertise may not exist at the recovery center or it is too expensive to duplicate recovery centers. This may also be applied to systems wherein the manufacturer does not want to disclose product details and would want to protect technical know-how.

3.3.1. Mathematical Representation for Recovery Model 3

This subsection illustrates all calculations needed for Recovery Model 3 to obtain the total cost and quantity received in good condition. Shipping cost (U) from node S_i to node $S_{(i+1)}$ is

$$U_{ij} = d_n \sum_{i=0}^{j} (A_{ij} B_{ij} + P_{Z,\mathrm{n}} + I_{i+1}) \tag{15}$$

Shipping cost for damaged products from node $S_{(i+1)}$ to the first stage (S_0) is

$$U_{i+1,0} = d_n X_{vnij} \sum_{i=0}^{i} B_{ij} * A_{ij} \tag{16}$$

The total shipping cost is the sum of Equations 15 and 16:

TABLE 2. PARAMETERS OF EXAMPLE FOR RECOVERY MODEL 2.

Parameter	Value	Parameter	Value	Parameter	Value
A_{ij} (mile)	500	$A_{i+1,r}$ (mile)	70	W_n ($)	30
B_{ij} ($)	0.03	$A_{r,i+1}$(mile)	70	d_n (unit)	100
X_{vnij} (%)	13	$P_{z,n}$ ($)	2	$B_{r,i+1}$ ($)	0.03
X_{1nij} (%)	4	$T_{1,n}$ ($)	3.5	$B_{i+1,r}$ ($)	0.03
X_{2nij} (%)	5	$T_{2,n}$ ($)	5.5	D_n ($)	2
X_{3nij} (%)	4	$O_{Z,n}$ ($)	2		
$\Omega_{3,n}$ ($)	15	I_{i+1} ($)	2		

Total shipping cost from the first node to the next node, and shipping cost from & to the recovery center can be calculated as follows:

$$U_{ij} = d_n(A_{ij}B_{ij} + P_{Z,n} + I_{i+1}) = 100\ (500 * 0.03 + 2 + 2) = \$1,900$$
$$U_{n+1,r} = B_{ij} * A_{i+1,r} * d_n X_{vnij} = 0.03 * 70 * (100 * 0.13) = \$27$$
$$U_{r,n+1} = B_{ij} * A_{r,i+1} * d_n(X_{1nij} + X_{2nij}) = 0.03 * 70 * 100\ (0.04 + 0.05) = \$18$$
$$U = U_{ij} + U_{i+1,r} + U_{r,i+1} = 1,900 + 27 + 18 = \$1,946$$

Total recovery cost for all types of damages can be obtained as follows:

$$T_{1,n} = d_n(X_{1nij}T_{1,n}) = 100\ (0.04 * 3.5) = \$14$$
$$T_{2,n} = d_n(X_{2nij}T_{2,n}) = 100\ (0.05 * 5.5) = \$27$$
$$D_{n,i} = d_n(X_{3nij}D_n) = 100\ (0.04 * 2) = \$8$$
$$O_{Z,n} = d_n(X_{1nij} + X_{2nij}) * O_{Z,n} = 100(0.04 + 0.05) * 2 = \$18$$
$$TRC = 100\ [(0.04 * 3.5) + (0.05 * 5.5) + ((.04 + .05) * 2)] + 8 = \$67$$

The number of good units received at node (i+1): $q_{i+1} = 100\left[\left(1 - 0.04\right)\right] = 96$

Sale price for type 3 damages: $\Omega_3 = d_i X_{3nij} * \Omega_{3,n} = 100 * 0.04 * 15 = \$60$

Unit cost for a good quantity received at node (i+1): $E = [1,946 + 67 + 3,000 - 60] / 96 = \$52$

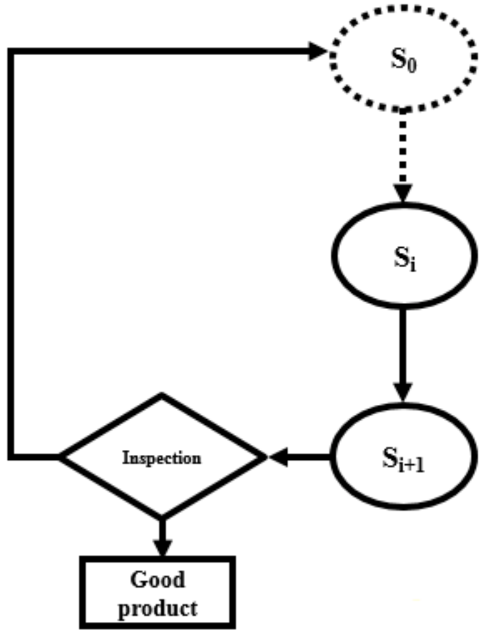

FIGURE 3. RECOVERY MODEL 3.

$$U = U_{ij} + U_{i+1,0} \tag{17}$$

After identifying the damaged products at $S_{(i+1)}$, they are shipped back to stage S_0 for repair. After sorting all damaged products at stage (S_0), all costs associated with damaged products are calculated to determine the total recovery cost. The repair cost associated with the recovery of type 1 and type 2 damaged products can be obtained by using Equations 7 and 8.

The repair cost associated with the recovery of type 3 damaged products is

$$T_{3,\mathrm{n}} = d_n(X_{3nij}T_{3,\mathrm{n}}) \tag{18}$$

The repackaging cost at the recovery center can be obtained by using Equation 10.

The total recovery cost is

$$TRC = d_n[(\sum_{v=1}^{3} X_{vnij}T_{\mathrm{v,n}}) + ((\sum_{v=1}^{3} X_{vnij}) * O_{Z,\mathrm{n}})] \tag{19}$$

The total quantity that arrives in good condition at node $S_{(n+1)}$, is

$$q_{i+1} = d_n\left[(1 - \sum_{v=1}^{3} X_{vnij})\right] \tag{20}$$

The cost per unit at node $S_{(n+1)}$ can be calculated as the sum of the total shipping cost, total recovery cost, and product cost divided by the number of good units that arrive at node $S_{(n+1)}$:

TABLE 3. PARAMETERS OF EXAMPLE FOR RECOVERY MODEL 3.

Parameter	Value	Parameter	Value	Parameter	Value
$V_{0,1}$(mile)	500	X_{3nij} (%)	8	W_n ($)	30
$V_{i,i+1}$(mile)	300	$A_{i+1,i}$ (mile)	300	d_n (unit)	100
B_{ij} ($)	0.03	$A_{i,0}$ (mile)	500	$T_{1,n}$($)	3.5
X_{vnij} (%)	16	$O_{z,n}$ ($)	2	$T_{2,n}$($)	5.5
X_{1nij} (%)	3	$P_{Z,n}$ ($)	2	$T_{3,n}$($)	7
X_{2nij} (%)	5	I_{i+1} ($)	2		

The total shipping cost from the first node to the next node, and shipping cost from the last stage to the main source can be calculated as follows:

$$U_{ij} = 100 * [((500 * 0.03) + 2)+((300 * 0.03) + 2)] = \$2,800$$

$$U_{n+1,0} = d_n X_{vnij} \sum_{i=0}^{i} B_{ij} * A_{ij} = 100 * 0.16[(300 * 0.03) + (500 * 0.03)] = \$384$$

$$U = U_{ij} + U_{i+1,0} = 2,800 + 284 = \$3,184$$

Total recovery cost for all types of damages is calculated as follows:

$$T_1 = d_n (X_{1nij} T_{1,n}) = 100(0.03 * 3.5) = \$10.5$$

$$T_2 = d_n (X_{2nij} T_{2,n}) = 100(0.05 * 5.5) = \$27.5$$

$$T_3 = d_n (X_{3nij} T_{3,n}) = 100(0.08 * 7) = \$56$$

$$O_{Z,n} = d_n (X_{1nij} + X_{2nij} + X_{3nij}) * O_{Z,n} = 100(.03 + .05 + .08) * 2 = \$32$$

$$TRC = 100 [(0.03 * 3.5) + (0.05 * 5.5) + (0.08 * 7) + (.03 + .05 + .08) * 2] = \$126$$

The number of good units received at the last node:

$$q_{i+1} = d_n \left[(1 - \sum_{v=1}^{3} X_{vnij}) \right] = 100 \ [(1 - 0.16)] = 84$$

The unit cost for a good quantity received at node (i+1):

$$E = [2,800 + 384 + 126 + 3,000] / 84 = \$75$$

$$E = [U_{ij} + U_{i+1,0} + TRC + d_n W_n] / q_{i+1} \quad (21)$$

3.3.2. Example for Recovery Model 3

This example illustrates the steps to calculate the unit cost and quantity received at the last node of this model. The parameters of the example for Recovery Model 3 are shown in Table 3. In summary, the total shipping cost is $3,520, the cost per unit is $68, the number of units of goods received at node $s_{(i+1)}$ is 98, and the lost product cost is $60.

3.4. Recovery Model 4

This model consists of two nodes and one recovery center, as shown in Figure 4. In this system, there is damage during shipping between the two nodes, and inspection occurs at node $S_{(i+1)}$. The damaged products are separated and shipped to the recovery center for repair. During inspection at the recovery center, only products with types 1 and 2 damage are recovered and those with type 3 damage are rejected. The recovered products are shipped back to node $S_{(i+1)}$. This model is used when the parts cannot be salvaged economically and/or may not have significant value. However, the repair and recovery of products with damages of Type 1 and Type 2 can be easily done and the product will have significant value as refurbished or can be sold as new.

3.4.1. Mathematical Representation for Recovery Model 4

The shipping cost (U) from node $S_{(i)}$ to node $S_{(i+1)}$ can be obtained by using Equation 1. The shipping cost for types 1 and 2 damaged products from node $S_{(i+1)}$ to the recovery center can be calculated as

$$U_{i+1,r} = B_{n+1,r} * A_{n+1,r} * d_n \left(\sum_{v=1}^{2} X_{vnij}\right) \quad (22)$$

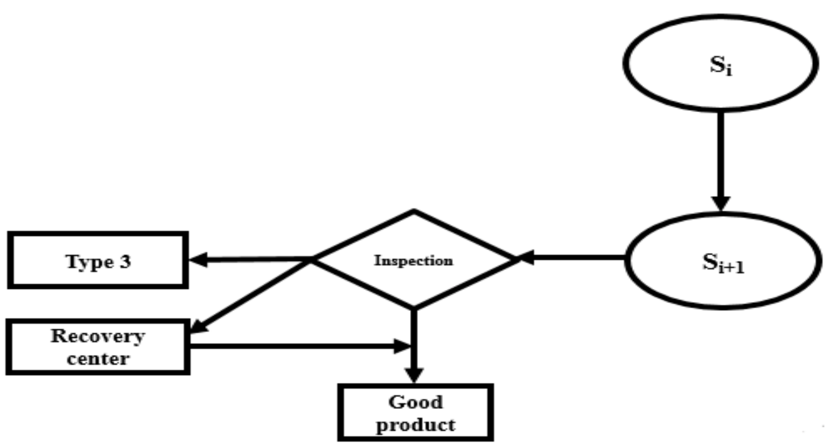

FIGURE 4. RECOVERY MODEL 4.

TABLE 4. PARAMETERS OF EXAMPLE FOR RECOVERY MODEL 4.

Parameter	Value	Parameter	Value	Parameter	Value
$A_{i,i+1}$(mile)	500	d_n (unit)	100	$O_{z,n}$($)	2
B_{ij} ($)	0.03	$A_{r,i+1}$(mile)	70	I_{i+1} ($)	2
X_{vnij} (%)	13	$A_{i+1,r}$ (mile)	70	W_n ($)	30
X_{1nij} (%)	4	$P_{z,n}$ ($)	2	$B_{r,i+1}$ ($)	0.03
X_{2nij} (%)	5	$T_{1,n}$ ($)	3.5	$B_{i+1,r}$ ($)	0.03
X_{3nij} (%)	4	$T_{2,n}$ ($)	5.5		

The total shipping cost from the first node to the next node, and shipping cost from the last stage to the recovery center & back can be calculated as follows:

$$U_{ij} = d_n(A_{ij}B_{ij} + P_{Z,n} + I_{i+1}) = 100\ ((500*0.03) + 2 + 2) = \$1,900$$
$$U_{i+1,r} = B_{i+1,r} * A_{i+1,r} * d_n(X_{1nij} + X_{2nij}) = 0.03*70*100\ (0.04 + 0.05) = \$19$$
$$U_{r,i+1} = B_{r,i+1} * A_{r,i+1} * d_n(X_{1nij} + X_{2nij}) = 0.03*70*100\ (0.04 + 0.05) = \$19$$
$$U = U_{ij} + U_{i+1,r} + U_{r,i+1} = 1,900 + 19 + 19 = \$1,938$$

The total recovery cost for types 1 and 2 damage is calculated as follows:

$$F_n = d_n(X_{3nij} * W_n) = 100\ (0.04*30) = \$120$$
$$O_{Z,n} = d_n(X_{1nij} + X_{2nij}) * O_{Z,n} = 100(0.04 + 0.05)*2 = \$18$$
$$TRC = 1\ 00[(0.04*3.5) + (0.05*5.5) + ((0.04+0.05)*2)] + 120 = \$180$$

The number of good units received at the last node: $q_{i+1} = d_n\left[(1 - X_{3nij})\right] = 100\ [1 - 0.04] = 96$

The cost per unit at node $S_{(i+1)}$ is the sum of the total shipping cost, total recovery cost, and product cost divided by the number of good units arrived:

$$E = [1,900 + 19 + 19 + 180 + 3,000]/96 = \$53$$

The shipping cost for repaired products from the recovery center back to node $S_{(i+1)}$ can be obtained by using equation (5).

The total shipping cost is the sum of shipping costs from Equations 1, 5, and 22:

$$U = U_{ij} + U_{i+1,r} + U_{r,i+1} \tag{23}$$

Equations 7 and 8 can be used to obtain repair costs for types 1 and 2 damage. The cost associated with type 3 damage at node $S_{(i+1)}$ can be obtained by

$$F_n = d_n(X_{3nij} * W_n) \tag{24}$$

Repackaging costs at the recovery center can be obtained by solving equation (10). The total recovery cost is the sum of the costs in Equations 7, 8, 10, and 24:

$$TRC = d_n[(\sum_{v=1}^{2} X_{vnij} T_{v,n}) + ((\sum_{v=1}^{2} X_{vnij}) * O_{Z,n})] + F_n \tag{25}$$

The total quantity that arrives in good condition at stage $S_{(i+1)}$, including recovered products, can be obtained by Equation 12. The cost per unit at stage $S_{(i+1)}$ is the sum of the total shipping cost, total recovery cost, and product cost divided by the number of good units arriving at node $S_{(i+1)}$:

$$E = [(U_{ij} + U_{i+1,r} + U_{r,i+1}) + TRC + d_n W_n] / q_{i+1} \tag{26}$$

3.4.2. Example for Recovery Model 4

This numerical example illustrates steps to calculate the unit cost and quantity received at the last stage of Recovery Model 4. The parameters for this numerical example are shown in Table 4.

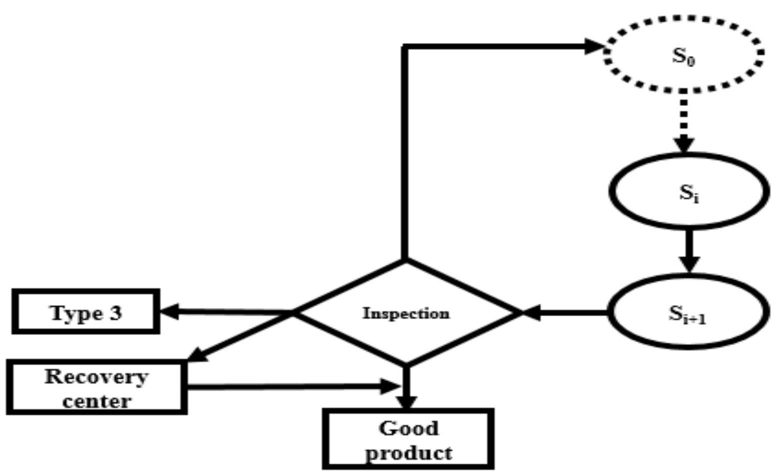

FIGURE 5. RECOVERY MODEL 5.

3.5. Recovery Model 5

This model reflects the system shown in Figure 5, which considers shipping from node S_i to node $S_{(i+1)}$ with one recovery center. Here, damage occurs during shipping between nodes $S_{(i)}$ and $S_{(i+1)}$, and the shipment is inspected at node $S_{(i+1)}$. The damaged products are separated and shipped to the recovery center for repair. At the recovery center, products with type 1 damage are recovered, products with type 2 damage are sent back to the first stage (S_0), and products with type 3 damage are rejected at the inspection stage. The recovered products are shipped back to node $S_{(n+1)}$.

3.5.1. Mathematical Representation for Recovery Model 5

This subsection illustrates the calculations needed to obtain the total cost and quantity received for Recovery Model 5. The shipping cost (U) from node S_i to node $S_{(i+1)}$ can be obtained by using Equation 15. The shipping cost for type 2 damaged products from node $S_{(i+1)}$ to the first source S_0 can be calculated as

$$U_{i+1,\,\mathrm{i}} = d_n X_{2nij} \sum_{i=0}^{j} B_{ij} * A_{ij} \tag{27}$$

The shipping cost for type 1 damage from $S_{(i+1)}$ to the recovery center is

$$U_{i+1,r} = B_{i+1,\,\mathrm{r}} * A_{i+1,r} * d_n X_{1nij} \tag{28}$$

The shipping cost for repaired products from recovery center *r* to $S_{(i+1)}$ is

$$U_{r,\,\mathrm{i+1}} = B_{r,\,\mathrm{i+1}} * E_{r,\,\mathrm{i+1}} * d_n X_{1nij} \tag{29}$$

The total shipping cost is the sum of shipping costs from Equations 15, 27, 28, and 29:

$$U = U_{ij} + U_{i+1,r} + U_{r,\,\mathrm{i+1}} + U_{i+1,\,\mathrm{i}} \tag{30}$$

After separating the damaged products at $S_{(i+1)}$, products with type 1 damage are shipped to the recovery center, products with type 2 damage are shipped to stage S_0 for repair, and products with type 3 damage at node $S_{(i+1)}$ are rejected. After sorting all damaged products, the costs associated with them can be calculated to determine the total recovery cost. Repair costs for products with type 1 damage can be obtained using Equation 7, and repair costs for products with type 2 damage can be obtained using Equation 8. Repackaging costs at the recovery center and at the main source are given by Equation 31.

$$O_{Z,\,\mathrm{n}} = \sum_{r}^{s_0} d_n (X_{1nij} + X_{2nij}) * O_{Z,\,\mathrm{n}} \tag{31}$$

The cost associated with type 3 damaged products at node $S_{(i+1)}$ can be obtained by solving equation 24.

The total recovery cost is the sum of costs from Equations 7, 8, 24, and 31.

$$TRC = d_n [(\sum_{v=1}^{2} X_{vnij} T_{1,\,\mathrm{n}}) + (\sum_{r}^{s_0} d_n (X_{1nij} + X_{2nij}) * O_{Z,\,\mathrm{n}})] + F_n \tag{32}$$

The total quantity that arrives in good condition at node $S_{(i+1)}$, including recovered products, is given by Equation 33.

$$q_{i+1} = d_n \left[1 - (\sum_{v=2}^{3} X_{\mathrm{vnij}}) \right] \tag{33}$$

TABLE 5. PARAMETERS OF EXAMPLE FOR RECOVERY MODEL 5.

Parameter	Value	Parameter	Value	Parameter	Value
$A_{0,i}$(mile)	500	$A_{i+1,r}$ (mile)	70	$O_{Z,n}$ ($)	2
$A_{i,i+1}$(mile)	300	$A_{r,i+1}$(mile)	70	$T_{1,n}$ ($)	3.5
B_{ij} ($)	0.03	$P_{z,n}$ ($)	2	$T_{2,n}$ ($)	5.5
X_{vnij} (%)	13	d_n (unit)	100	$B_{r,i+1}$ ($)	0.03
X_{1nij} (%)	5	I_{i+1} ($)	2		
X_{2nij} (%)	7	$B_{i+1,r}$ ($)	0.03		
X_{3nij} (%)	1	W_n ($)	30		

The total shipping cost from the first node to the next node, and shipping cost from the last node to the recovery center and back can be calculated as follows:

$$U_{ij} = d_n \sum_{i=0}^{j} (A_{ij}B_{ij} + P_{Z,n} + I_{i+1}) = 100 * ((500 * 0.03 + 2 + 0) + (300 * 0.03 + 0 + 2)) = \$2,800$$

$$U_{i+1,r} = B_{i+1,r}A_{i+1,r} * d_n X_{1nij} = 0.03 * 70 * 100 * 0.05 = \$11$$

$$U_{r,i+1} = B_{r,i+1}A_{r,i+1} * d_n X_{1nij} = 0.03 * 70 * 100 * 0.05 = \$11$$

$$U_{i+1,0} = d_n X_{2nij} \sum_{0}^{i} B_{ij} * A_{ij} = 100 * 0.07((0.03 * 300)+(0.03 * 500)) = \$168$$

$$U = 1,700 + 1,100 + 11 + 11 + 168 = \$2,989$$

The total recovery cost for the damage product is calculated as follows:

$$F_n = d_n (X_{3nij} * W_n) = 100\ (0.01 * 30) = \$30$$

$$O_{Z,n} = \sum_{r}^{s_0} d_n (X_{1nij} + X_{2nij}) * O_{Z,n} = 100\ (0.05 + 0.07) * 2 = \$24$$

$$TRC = 100\ [(0.05 * 3.5) + ((0.07 * 5.5) + (0.05 + 0.07) * 2)] + 30 = \$110$$

The number of good units received at the last node:

$$q_{i+1} = d_n \left[1 - (X_{2nij} + X_{3nij})\right] = 100\ [1 - (0.07 + 0.01)] = 92$$

The cost per unit at node $S_{(i+1)}$: $E = [2,989 + 110 + 3,000] / 92 = \$66$

The cost per unit at stage $S_{(i+1)}$ is the sum of the total shipping cost, total recovery cost, and product cost divided by the number of good units arriving at node $S_{(i+1)}$.

$$E = [U_{ij} + U_{i+1,r} + U_{r,\,i+1} + U_{i+1,\,i} + TRC + d_n W_n] / q_{i+1} \tag{34}$$

3.5.2 . Numerical Example 5 for Recovery Model 5

This example illustrates steps to calculate the unit cost and quantity received at the last stage of this model. The parameters for this numerical example are shown in Table 5.

IV. CASE STUDIES

Three case studies that incorporate the recovery models are used to demonstrate the use of the recovery models in decision making. Case study 1 demonstrates the use of the recovery models to select the best route and to determine the best option for locating the recovers center. Case Study 2 is used to show the use of the recovery models in determining the best location for inspection. Case Study 3 demonstrates the use of recovery models to determine the best plan of action. In this case study, the recovery models are applied to determine the decision as to whether the products should be repaired at the recovery station or at the factory at Stage S_0. These case studies demonstrate the use of the recovery models in various situations and its use in designing the supply chain.

4.1. Case Study 1

Here, a case study is used to demonstrate the effectiveness of the proposed methodology. In this study, a company has one product P_1 and uses two routes for shipping the product. The product cost is \$30, and the customer demand is 1,000 units. The shipping cost depends on the type of transportation (truck, train, or ship). Figure 6 shows a transportation network that consists of two routes (R_1 and R_2), a manufacturer (M), four facilities (F1, F2, F3, and F4), two recovery centers (RC1, and RC2), and one retailer (G). Each route has different methods of transportation, distances, and shipping costs. The associated distances and shipping costs per mile are shown in Figure 6. Tables 6 and 7 shows the recovery system parameters and damage probability for each path, respectively, for this case study.

4.1.1. Results and Analysis for Case Study 1

The models were developed and solved using the total enumeration strategy and MATLAB. This case study was used to validate the proposed models. By applying the proposed models, the units of goods and cost per unit received at the final destination for all recovery models were determined. When applying Recovery Model 1, the optimal quantity received at the final destination was 860 units at a cost per unit of \$72 by selecting route R_1. When Recovery Model 2 was applied, the maximum quantity arriving at the final destination was 904 units at a cost per unit of \$68 when using route R_1. In this case study, the better option is to select route 2 for the supply chain and apply recovery model 2 at Stage F_4.

4.2. Case Study 2

In this study, the supply chain network shown in Figure 8 is considered, which consists of five stages. There is high damage that occurs during stage S_0 to S_1, and shipping cost from stage S_1 to S_2 is very expensive and the distance between S_1 and S_2 is also high. Inspection at stage S_1 is less expensive than the inspection at the retailer stage as shown in Figure 7. In this case study there are two options for shipping product from stage S_0 to retailer stage. In the first option, inspection does not occur until the product reaches the retailer. The second option is to perform inspection at stage S_1 and return the damaged product to the first stage S_0 for recovering. The repair cost per product at stage S_0 is \$5.50. The parameters for this study are shown in Table 8.

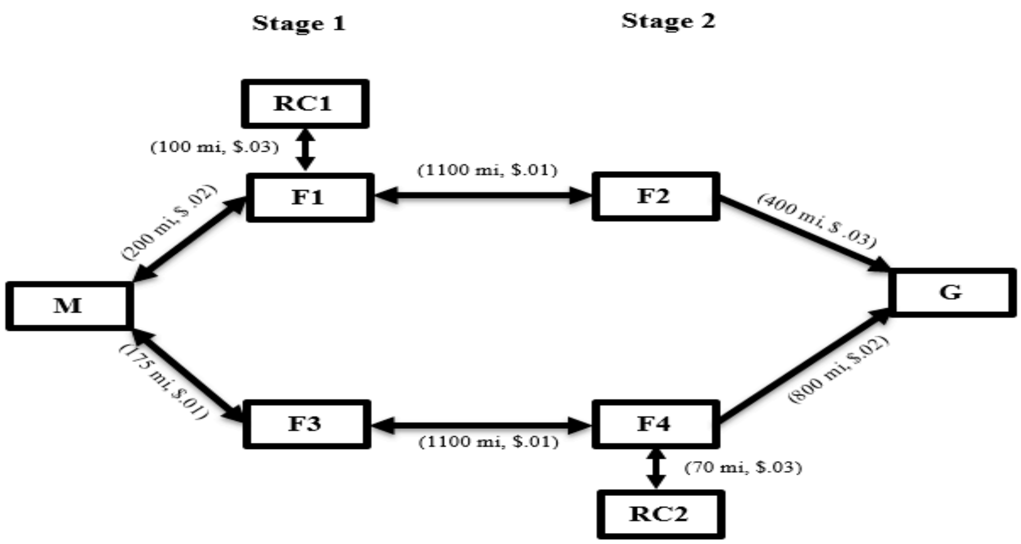

FIGURE 6. TRANSPORTATION NETWORK FOR CASE STUDY 1.

TABLE 6. PARAMETERS OF RECOVERY SYSTEM IN CASE STUDY 1.

Parameter	Value (\$)	Parameter	Value (\$)
Repair cost for X_{1nij} damage at RC1	3.5	Repair cost for X_{3nij} damage at RC2	12
Repair cost for X_{2nij} damage at RC1	5.5	Repackaging cost at RC1	1.5
Repair cost for X_{3nij} damage at RC1	10	Repackaging cost at RC2	3
Repair cost for X_{1nij} damage at RC2	4	Disassembly cost/ product	2
Repair cost for X_{2nij} damage at RC2	7	Inspection cost	0.25

TABLE 7. DAMAGE PROBABILITY FOR EACH PATH IN CASE STUDY 1.

Path	Damage Probability for Type Z Packaging		
	X_{1nij} (%)	X_{2nij} (%)	X_{3nij} (%)
M-F1	3.40	1.45	0.70
M-F3	2.30	5.50	1.30
F1-F2	3	0.45	1.20
F3-F4	1.30	5.50	1.40
F2-J	2.40	1.60	0.55
F4-J	2.00	2.60	1.50

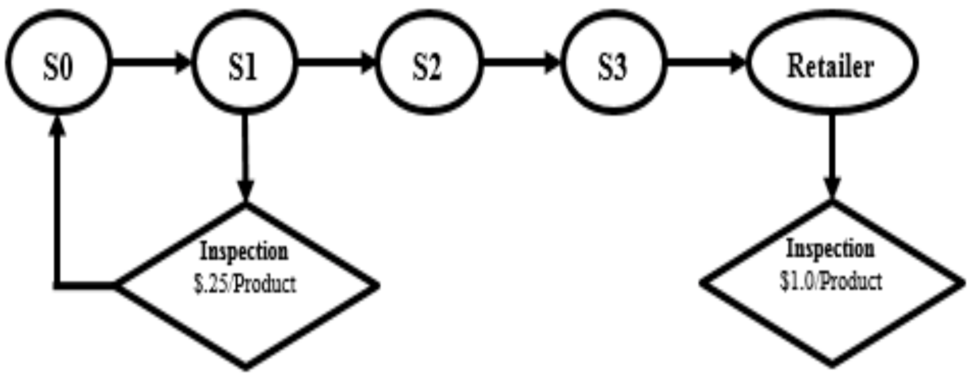

FIGURE 7. TRANSPORTATION NETWORK FOR CASE STUDY 2.

TABLE 8. DESIGN PARAMETERS FOR CASE STUDY 2.

Stage	S_1	S_2	S_3	Retailer
Distance (mile)	200	500	100	150
Cost per mile ($)	0.15	1	0.25	0.10
Damage (%)	30	5	3	6

4.2.1. Results and Analysis for Case Study 2

When applying option one, in which inspection occurs at the last stage, the total shipping cost is $57,300. The unit cost is $1077 with 56 good units received at the last stage for every 100 units that are shipped. When applying the second option, the total shipping cost is $57,963. The unit cost is $1093 with 56 good units received at the last stage for every 100 units that are shipped. After obtaining the results for both options, it is clear that performing inspection at stage S_1 and return the damaged products to stage S_0 for recovering is more cost efficient. Thus in this case study, it is better for the inspection station to be located at stage S_1.

4.3. Case Study 3

In this case study, the supply chain network shown in Figure 8 is considered. This supply chain network consists of five stages. Inspection is performed at stage S_2. The repair cost at stage S_0 is three dollars while stage S_2 repair cost is $22. In this study, there are two options while shipping product from stage S_0 to retailer stage. The first option is perform inspection at Stage S_2 and recover the damaged products. The second option is to return the damaged product to the first stage 'S_0' for recovering. The parameters for this study are shown in Table 9.

4.3.1. Results and Analysis for Case Study 3

When applying option one, the total shipping cost is $26,425. The unit cost is $327 with 91 good units received at the last stage for every 100 units that are shipped. By applying the second option the total shipping cost is $27,740. The unit cost is $390 with 79 good units received at the last stage for every 100 units that are shipped. After obtained the result for both options, it is clear that repairing the damaged products at stage S_2 it is more cost efficient. Thus in this case study, it is better for defective products to be shipped back to stage S_0.

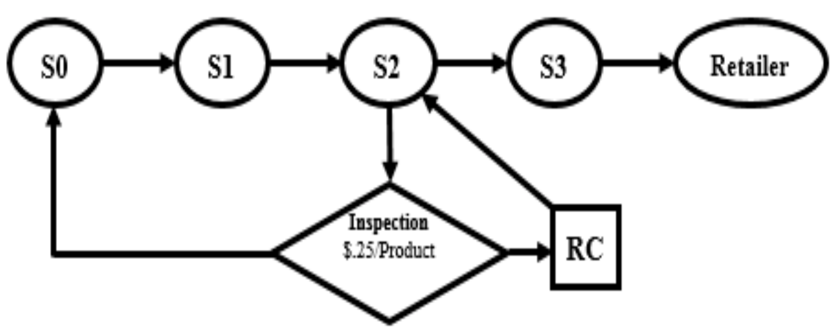

FIGURE 8. TRANSPORTATION NETWORK FOR CASE STUDY 3.

TABLE 9. DESIGN PARAMETERS FOR CASE STUDY 3.

Stage	S_1	S_2	S_3	Retailer
Distance (mile)	200	400	100	150
Cost per mile ($)	0.15	0.45	0.25	0.10
Damage (%)	7	5	3	6

V. CONCLUSIONS AND FUTURE WORK

In this research, different recovery models were developed to maximize quantity of products at the final destination in order to meet demand by considering different recovery scenarios. This research proposed a new approach for recovering different types of damage that occur during transit. Since the amount and type of damage is different at each stage of the supply chain network, different models for recovering the products were developed, depending on the type of damage that occurred. Three case studies were applied to demonstrate the use of the proposed recovery models when different recovery scenarios and damage types occur during shipping. Each case study incorporated different recovery models to determine the best option among the provided ones. A more comprehensive methodology which incorporates all recovery models as an option is being developed to help in designing the supply chain. In future work, the models could also be expanded to consider multi-suppliers and impact of improved packaging in order to reduce damage during shipping and transportation cost.

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