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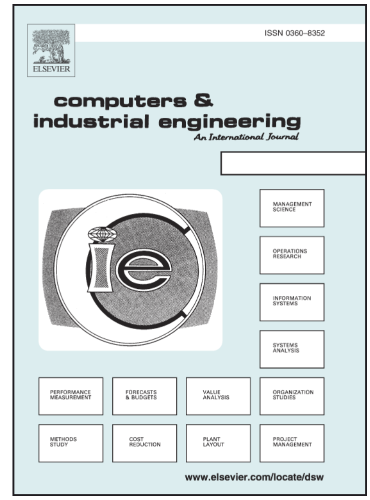

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Effect of Carbon Tax on Reverse Logistics Network Design

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Abstract

Reverse logistics network design (RLND) is getting momentum as more organizations realize the benefits of recycling or remanufacturing of their end-of-life products. Similarly, there is an impetus for organizations to become more environmentally conscious or green. This environmental context has driven many organizations to invest in green technologies, with a recent emphasis on reducing greenhouse gas emissions. This environmental investment situation and decision can be addressed through the integration of facility location, operational planning, and vehicle type selection, while simultaneously accounting for carbon emissions from vehicles, inspection centers, and remanufacturing centers in a reverse logistics (RL) context. In the current study, we present a mixed-integer linear programming (MILP) model to solve a multi-tier multi-period green RL network, including vehicle type selection. This research integrates facility locations, vehicle type selection with emissions producing from transportation and operations at various processing centers. Prior research does not account for carbon emissions for this design problem type. Valuable managerial insights are obtained when incorporating carbon emissions cost.

Keywords: Reverse Logistics; Remanufacturing; Network Design; Mixed Integer Linear Programming; Carbon Footprint

1. Introduction

Throughout the history of corporate environmentalism, environmental actions and concerns have evolved from a localized, pollution emissions perspective, to a global concern on general environmental sustainability through such efforts as the United Nations Global Compact (Kell, 2003). During the past three decades, there have been many international conferences and treaties, including the recent Conference of Parties (COP) emphasizing the need to rein in global climate change greenhouse gas (GHG) emissions (Boucher et al., 2016).

There is a consensus among world leaders for the need to limit GHG emissions. Global organizations recognize the need to consider inter-generational sustainability as a means of survival, given that a significant share of the economy heavily burdens the natural resource base, which is continuously depleting. Among many popular corporate environmental sustainability initiatives remanufacturing and its supporting activities will play a vital role to extend the life of resources and materials; while seeking to limit pollutant emissions (Kerr & Ryan, 2001; Diener & Tillman, 2015). In addition to this environmental benefit, business benefits also exist. Firms can strategically distinguish themselves from competitors by reducing their costs, adding value to their supply chain and end customers while achieving environmental sustainability through RL and remanufacturing efforts (Kumar, Chinnam, & Murat, 2017).

Remanufacturing refers to "activities that restore used products or their major modules to an operational condition for use in place of a new product or other channels" (e.g., spare parts) (Guide, 2000). The U.S. Environmental Protection Agency (EPA) advocates remanufacturing practice as an energy-efficient, economical and environmentally friendly approach for reducing the industrial waste (US EPA, 1997). Moreover, it is also worth for firms to overlook the factors that influence the emissions produced in RL network and its operations. Factors that can influence emissions include the size of remanufacturing, collection, and inspection center facilities, vehicle type, vehicle loads, and the distance they travel (Cachon, 2014; Benjaafar et al., 2013).

RLND has traditionally focused on network, logistics processes, and managing efficient returns. However, with an ever-increasing interest in corporate environmental sustainability measures, firms are not only aiming for an efficient network design but also carbon footprint reduction, seeking the complete transformation of the supply chain into a green and closed-loop supply chain (CLSC) (Devika, Jafarian, & Nourbakhsh, 2014; Sarkar, Ullah, & Kim, 2017). Greening, the supply chain goes beyond complying with environmental legislation and regulations; closing the supply chain loop leads to the efficient returns management and remanufacturing includes additional environmental and business benefits.

RL a necessity for effective remanufacturing, includes "the process of planning, implementing and controlling reverse flows of raw materials, in-process inventory, packaging, and finished goods, from manufacturing and distribution or use point, to the point of recovery or point of proper disposal" (Tibben-Lembke, 1998; Meade, Sarkis, & Presley, 2007). RL activities include the following tasks: creating inspection and remanufacturing centers, managing center throughput to satisfy demand, choosing between storing as inventory or purchasing new products or disposing of returned products. An important aspect to these RL activities, that has seldom been investigated in the literature is vehicle type selection and has been recognized as needed direction research in vehicle allocation within greening of supply chains (Lin et al. 2014). The Vehicle type selection problem can be altered to find an optimal number of vehicles of different type to meet customer demand while minimizing total transportation cost. These goals have evolved to include more efficient energy usage and carbon emissions reductions. The inclusion of carbon emission costs at various inspection and remanufacturing centers and vehicle types can substantially alter the existing dynamics of these problems. Thus, the green reverse supply chain problem should consider RL, vehicle type selection, and carbon emissions.

Early researches in the area of RLND have considerably explored the relation between traditional forward and reverse logistics. These studies focused on the topological and methodological level. At topological level aim was to analyze the effect of product recovery on the network structure. It was highlighted that the used products availability for recovery is far more difficult to control than the traditional supply chain resources. Hence, there might be a substantial mismatch between demand and supply regarding timing and quantity in a recovery network. Moreover, in general, used products availability and quality are not known in advance. Thus uncertainty in supply becomes a key characteristic for recovery networks (Fleischmann & Kuik, 2003).

At the methodological level, the coordination between exogenous demand and supply is represented by constraints makes things more difficult than traditional forward logistics network design. MILP approach is mostly used in modeling facility location problem in the logistics network. Numerous researchers have adapted an MILP approach to model problems in RL context (Fleischmann et al., 1997).

Now, it is important to describe our contributions to the body of literature.

i. Developing an MILP model to find optimal inspection and remanufacturing locations.
ii. Incorporated selection of appropriate vehicle type options to carry the goods among centers in the reverse supply chain. These options include trucks with various capacities.
iii. Keeping a bigger picture of the green supply chain, we have accounted for carbon emissions from vehicles, facilities such as inspection and remanufacturing centers in an RL context.

iv. Further, as mentioned earlier "uncertainty a major characteristic of recovery networks", we considered operating costs at inspection and remanufacturing centers to be time-varying. A dynamic product return factor is also being modelled. This dynamic decision environment is capable of incorporating uncertainties reflected in such dimensions as seasonally varying costs.

In totality, we model a multi-period, green reverse supply chain problem to address interrelated decisions including a number of inspection and remanufacturing centers, number, and type of vehicles, disposal and inventory quantities, and amount of virgin product quantity purchase in each period. To determine the environmental parametric influences on the reverse supply chain design investigation, decisions made with and without carbon emission cost inclusion are included in the analysis.

The paper is structured in the following way: Section 2 provides a foundational literature survey placing this study in the broader and emergent research literature on designing green supply chains and in this case greening of multi-tier reverse supply chains. Section 3 introduces the problem definition for our research setting. Section 4 provides details of MILP formulation for the green reverse supply chain. We present results along with discussions in section 5. In Final section, the conclusions, as well as the future scope of this paper, are presented.

2. Literature review

Mandatory regulations, social image, and building market competitive advantages are driving manufacturers to integrate RL into the supply chain. Merging RL into existing logistics design is growing within logistics and supply chain strategic design research (Fleischmann et al. 2001). For solving the RLND problem, various modeling approaches such as mixed-integer location, continuous approximation, and stochastic location models have been developed (Fleischmann et al. 2004). The extant research has introduced models with significant complexity, including various analytical modeling and pricing models with an explicit focus on business and pricing concerns (Pokharel & Mutha, 2009; Govindan & Soleimani, 2017). Interestingly, in many of these modeling efforts, environmental issues typically took a backseat to economic issues. For example, Srivastava, (2008) utilized combinatorial optimization to make various decisions like reuse, refurbish, remanufacture to maximize profit.

Multi-period RL network models focusing on long-term dimensions allow for better strategic decision analysis in some research (Lee & Dong 2009). This literature also incorporated the dynamic nature of locations allocation and various costs, such as operating costs. Yet, integrating quality of used products into these models is limited. Further information can be gleaned from considering facility location analyses with unlimited capacity in an RL network, one of which has been applied to collecting end-of-life vehicles (Cruz-rivera & Ertel 2009). From these results, it was found that transportation cost is the determinant factor for the RL network. Another avenue of research focuses on solving product characteristics and designs in RL network, where MILP formulations seem like a tool of choice (Das & Chowdhury 2012). Rahimi & Ghezavati, (2018) designed an RL network to recycle the construction and demolition waste with consideration of the social impact and environmental effect along with cost in a multi-period setting. Özceylan et al. (2017) developed a model over a finite planning horizon to design CLSC for recycling end-of-life vehicles in turkey. Various stages of RL, such as the collection of core returns, components recovery, and producing products with various quality levels have been considered as necessary modelling aspects (Das & Chowdhury, 2012). These issues are further integrated into the models in this paper.

The emission cost due to transportation and operations at facilities is an important aspect in RLND. Recent expansion and consideration of broad logistics network designs are integrating both forward and reverse flows with a goal to reduce the carbon footprint, and total cost through the supply chain is starting to become integrated into the decision-making environment (Choudhary et al. 2015); Chaabane et al. 2012). Fahimnia et al. (2013) evaluated and analyzed the effect of carbon emission on forward and reverse supply chain and also validated for an Australian based company (TexF). Carbon footprint based reverse logistic designs included tools focused on transportation characteristics as well (Kilic, Cebeci, & Ayhan, 2015; Bing et al. 2014). Guo et al. (2017) developed a model for network and route planning of an integrated forward and reverse logistics. Parametric consideration and valuation using carbon markets and credit may play an important role for design purposes since these tradeable permits can affect various cost structures and technological decisions in EL designs (Kannan et al. (2012)). In this previous work, authors considered carbon emissions only because of transportation or processing at facilities. However, in this paper, the carbon emissions from both activities are considered.

Multi-period reverse logistics network designs have included inventory as a major decision characteristic, balancing inventory and disposal costs (Alumur et al. (2012)). Balancing the logistics network design decisions may also include the level of new versus reused modules in manufacture (Mutha & Pokharel (2009)). These dimensions are also introduced in this study, further expanding the decision environment by incorporating broader realistic complexities.

There have been several papers which have focused on routing problems for reverse network design. A vehicle routing problem (VRP) with simultaneous pickup and delivery has been introduced by Hezer and Yakup (2010) and solved using bacterial foraging optimization algorithm. A vehicle routing problem was used to address a South Korean case (Kim et al. 2009) using a Tabu search heuristic method for end-of-life products in RL. Carbon emissions based logistic-network planning was also completed (Wanke et al. 2015) with two types of costs – transportation and stock holding cost in a network - being considered integrating environment related expenses. Kassem & Chen, (2013) introduced an RL VRP problem with time windows where return/pickup of products are allowed to happen only during certain time periods and have tried to address the problem using heuristics and tried to improve the runtime of results by using simulated annealing procedure.

In these previous studies mentioned above, studies considered either Vehicle type selection or carbon emissions but did not consider these elements simultaneously. In practical situations, the cost parameters, quality, and quantity of returns vary over different planning periods. These dynamic characteristics are incorporated into the model by considering it as a multi-period problem. In logistics or supply chains, transportation plays a major role. To reduce costs and manage emissions due to the transportation, vehicle type selection is integrated into the model.

A green image is achieved by implementing the green technologies for transportation and processing of materials at facilities. The need to investigate the relationships between green supply chain and sustainability in RL has been well established (Govindan et al. 2016; Zhao & Li, 2016). Further, in today's context, it is certain that the transport sector needs to shift their attention from minimizing total operational costs to sustainability. Motivated by such findings, this integrated dynamic research is the attempt of its kind in the literature to incorporate aforementioned parameters to formulate an MILP model for RLND to help the practitioner community by providing valuable managerial insights. Also, it imparts insights for researchers for modelling and evaluating results in this environment.

3. Problem Description

The network schematic for a reverse supply chain, which can be viewed as a four-tier supply chain, is presented in Figure 1. The first tier represents the number of fixed collection centers responsible for collecting and storing the used products from customers. Inspection centers appear in the second tier. These facilities inspect and classify used products into different categories – a triage based on their quality. Products with good quality are remanufactured by the OEMs in the next tier, while products unsuitable for remanufacturing are disposed. The third tier includes remanufacturing centers for recovering used products that arrive from the inspection centers. In the third tier, new products are purchased to satisfy the demand when there is lack of sufficient cores to process. Finally, the fourth tier represents several fixed markets which create demands for products, and return a portion of used products to collection centers.

<< Insert Figure 1 here >>

The objective is to maximize the total firm's profit including revenue from the sale of products and costs such as opening, carbon emissions and operating expenses of inspection and remanufacturing centers, disposal cost, inventory holding cost, transportation and emission cost from vehicles and purchase cost of virgin products. We assume here that remanufacturing is an attractive option, and thus, firms try to meet most of the demand using the remanufactured product. In the remanufactured products shortage case, firms are assumed to purchase virgin products. This cost can be used as the manufacturing cost of virgin products.

In this setting, it is considered that collection centers are the same as markets and fixed. The demand for products exists only in the markets. Moreover, core returns are assumed to be depending on previous periods demand, and the returned products quality is presented in terms of yield-factor at inspection centers. The returned products are inspected at the inspection center, and an associated yield is determined. In most remanufacturing industries, yield issues are customary given all core returns are not suitable for remanufacturing. Such factors are attributed frotom the customer product usage and its nature and can control yield to somewhat by firms. This yield differs from one inspection center to another based on the type of technologies used for inspecting returns.

We considered disposal and inventory decisions, only at inspection centers with corresponding disposal and inventory holding costs respectively. Since this study's focus is on strategic level decisions, operational decisions and bill of materials are not presented.

Some assumptions considered in the model include:

- The supply of returns and demand are deterministic and dynamic.
- The quality of the products is deterministic and dynamic.
- No inventory is present at inspection centers in the initial and final periods.
- The selling price of the remanufactured product is the same as the new product and constant throughout the planning horizon (Gan et al. 2015).
- Location of collection centers/markets is known in advance.

4. Mathematical Modelling

In this section, a MILP model was proposed to design a multi-echelon RL network. The model includes many practical significant features such as carbon emissions, a return factor, yield and a multi-period setting along with disposal, inventory, purchase decisions and vehicle type selection for transportation. The model notations including sets, parameters and decision variables are presented below.

4.1. Notation

Sets

T – Planning horizon time periods.

V - Set of vehicles of the different type available for transport.

I - Set of potential inspection centers.

C - Set of collection centers (same as markets).

R - Set of potential locations remanufacturing centers.

M - Set of markets.

Parameters

P - The selling price of the product per unit.

λ - Yield factor at inspection center.

S_c^t - Returns at collection center c ∈ C in period t ∈ T ($S_c^t = f_c^t D_m^{t-1}$).

$CAPI_i$ - Maximum capacity of an inspection center i ∈ I.

$CAPR_r$ - Maximum capacity of a remanufacturing center r ∈ R.

f_c^t - Return factor at collection center c ∈ C in period t ∈ T.

$VCAP_v$ - Maximum capacity of a vehicle of type v ∈ V.

SCI_i - Setup cost to open an inspection center i ∈ I.

SCR_r - Setup cost to open a remanufacturing center r ∈ R.

DC – Unit disposal cost.

PC – Unit purchase cost.

IC – Unit inventory holding cost.

OCR_r^t - Cost to process one unit at remanufacturing center r ∈ R in period t ∈ T.

OCI_i^t - Cost to inspect one unit at inspection center i ∈ I in period t ∈ T.

E_v - Carbon emissions per unit distance for vehicle type v ∈ V.

EI_i - CO_2 emissions per unit at the inspection center i ∈ I.

ER_r - CO_2 emissions per unit at the remanufacturing center r ∈ R.

Ω - Carbon emissions costs per unit ton of CO_2.

dC_{ci} - Distance between collection center c ∈ C and inspection center i ∈ I.

dI_{ir} - Distance between inspection center i ∈ I and remanufacturing center r ∈ R.

dR_{rm} - Distance between remanufacturing center r ∈ R and market m ∈ M.

FTC_v - Fixed cost for hiring vehicle type v ∈ V.

VTC_v - Variable cost to travel travelling unit distance for vehicle type v ∈ V.

D_m^t - Demand at market m ∈ M in period t ∈ T.

Decision variables

xC_{civ}^t - Product quantity moved from c ∈ C to i ∈ I in t ∈ T using v ∈ V.

xI_{irv}^t - Product quantity moved from i ∈ I to r ∈ R in t ∈ T using v ∈ V.

xR_{rmv}^t - Product quantity moved from r ∈ R to m ∈ M in t ∈ T using v ∈ V.

z_r^t - 1 if remanufacturing center r ∈ R is open in period t ∈ T, otherwise 0

y_i^t - 1 if inspection center i ∈ I is open in period t ∈ T, otherwise 0

NC_{civ}^t - Vehicles of type v ∈ V required for transporting products between c ∈ C and i ∈ I in t ∈ T.

NI_{irv}^t - Vehicles of type v ∈ V required for transporting products between i ∈ I and r ∈ R in t ∈ T.

NR_{rmv}^t - Vehicles of type v ∈ V required for transporting products between r ∈ R and m ∈ M in t ∈ T.

IQ_i^t - Inventory quantity at i ∈ I in t ∈ T.

DQ_i^t -Disposal quantity at i ∈ I in t ∈ T.

PQ_r^t - Purchase amount at r ∈ R in t ∈ T.

4.2. Formulation

Given the notation and decision variables mentioned above, the MILP formulation for the proposed network seeks to maximize total network profitability.

Objective:

$$Maximize\ \ Z = p\sum_{r\in R}\sum_{m\in M}\sum_{v\in V}\sum_{t\in T} xR_{rmv}^{t} - \left(\sum_{t\in T}\left[\sum_{i\in I} SCI_i\left(y_i^t - y_i^{t-1}\right) + \sum_{r\in R} SCR_r\left(z_r^t - z_r^{t-1}\right)\right]\right.$$

$$+\sum_{t\in T}\sum_{v\in V}\left[\sum_{c\in C}\sum_{i\in I} OCI_i^t xC_{civ}^t + \sum_{i\in I}\sum_{r\in R} OCR_r^t xI_{irv}^t\right] + \sum_{t\in T}\sum_{i\in I} DQ_i^t DC + \sum_{t\in T}\sum_{i\in I} IQ_i^t IC + \sum_{t\in T}\sum_{r\in R} PQ_r^t PC$$

$$+\sum_{t\in T}\sum_{v\in V}\left[\sum_{c\in C}\sum_{i\in I} NC_{civ}^t\left(FTC_v + VTC_v dC_{ci}\right) + \sum_{i\in I}\sum_{r\in R} NI_{irv}^t\left(FTC_v + VTC_v dI_{ir}\right)\right.$$

$$\left.+\sum_{r\in R}\sum_{m\in M} NR_{rmv}^t\left(FTC_v + VTC_v dR_{ci}\right)\right] + \Omega\left[\sum_{t\in T}\sum_{v\in V}\left(\sum_{c\in C}\sum_{i\in I} dC_{ci} NC_{civ}^t E_v\right.\right.$$

$$\left.\left.\left.+\sum_{i\in I}\sum_{r\in R} dI_{ir} NI_{irv}^t E_v + \sum_{r\in R}\sum_{m\in M} dR_{rm} NR_{rmv}^t E_v\right)\right] + \Omega\left[\sum_{t\in T}\sum_{v\in V}\left(\sum_{c\in C}\sum_{i\in I} EI_i xC_{civ}^t + \sum_{i\in I}\sum_{r\in R} ER_r xI_{irv}^t\right)\right]\right) \tag{1}$$

Constraints:

$$\sum_{i\in I}\sum_{v\in V} xC_{civ}^t = S_c^t \qquad \forall c\in C, \forall t\in T \tag{2}$$

$$\lambda_i \sum_{c\in C}\sum_{v\in V} xC_{civ}^t = \sum_{r\in R}\sum_{v\in V} xI_{irv}^t + IQ_i^t + DQ_i^t \qquad \forall i\in I, \forall t\in 1 \tag{3}$$

$$\lambda_i \sum_{c\in C}\sum_{v\in V} xC_{civ}^t = \sum_{r\in R}\sum_{v\in V} xI_{irv}^t + IQ_i^t - IQ_i^{t-1} + DQ_i^t \qquad \forall i\in I, \forall t\in 2..T \tag{4}$$

$$\sum_{i\in I}\sum_{v\in V} xI_{irv}^t + PQ_r^t = \sum_{m\in M}\sum_{v\in V} xR_{rmv}^t \qquad \forall r\in R, \forall t\in T \tag{5}$$

$$\sum_{r\in R}\sum_{v\in V} xR_{rmv}^t = D_m^t \qquad \forall m\in M, \forall t\in T \tag{6}$$

$$\sum_{c\in C}\sum_{v\in V} xC_{civ}^t \le y_i^t CAPI_i \qquad \forall i\in I, \forall t\in T \tag{7}$$

$$\sum_{i\in I}\sum_{v\in V} xI_{irv}^t \le z_r^t CAPR_r \qquad \forall r\in R, \forall t\in T \tag{8}$$

$$NC_{civ}^t \ge xC_{civ}^t / VCAP_v \qquad \forall c\in C, \forall \mathrm{i}\in I, \forall \mathrm{v}\in V, \forall t\in T \tag{9}$$

$$NI_{irv}^t \ge xI_{irv}^t / VCAP_v \qquad \forall \mathrm{i}\in I, \forall \mathrm{r}\in R, \forall \mathrm{v}\in V, \forall t\in T \tag{10}$$

$$NR_{rmv}^t \ge xR_{rmv}^t / VCAP_v \qquad \forall r\in R, \forall \mathrm{m}\in M, \forall \mathrm{v}\in V, \forall t\in T \tag{11}$$

$$y_i^t \ge y_i^{t-1} \qquad \forall t\in T, \forall i\in I \tag{12}$$

$$z_i^t \geq z_i^{t-1} \qquad \forall t \in T, \forall r \in R \qquad (13)$$

$$y_i^1 = 0 \qquad \forall i \in I \qquad (14)$$

$$z_r^1 = 0 \qquad \forall r \in R \qquad (15)$$

$$IQ_i^1 = 0 \qquad \forall i \in I \qquad (16)$$

$$IQ_i^T = 0 \qquad \forall i \in I \qquad (17)$$

$$y_i^t \in \{0,1\} \qquad \forall t \in T, \forall i \in I$$

$$z_r^t \in \{0,1\} \qquad \forall t \in T, \forall r \in R$$

$$IQ_i^t \geq 0 \qquad \forall i \in I, \forall t \in T$$

$$DQ_i^t \geq 0 \qquad \forall i \in I, \forall t \in T$$

$$PQ_r^t \geq 0 \qquad \forall i \in I, \forall t \in T$$

$$NC_{civ}^t \geq 0 \qquad \forall c \in C, \forall \mathrm{i} \in I, \forall \mathrm{v} \in V, \forall t \in T$$

$$NC_{irv}^t \geq 0 \qquad \forall \mathrm{i} \in I, \forall \mathrm{r} \in R, \forall \mathrm{v} \in V, \forall t \in T$$

$$NC_{rmv}^t \geq 0 \qquad \forall r \in R, \forall \mathrm{m} \in M, \forall \mathrm{v} \in V, \forall t \in T$$

$$xC_{civ}^t \geq 0 \qquad \forall c \in C, \forall \mathrm{i} \in I, \forall \mathrm{v} \in V, \forall t \in T$$

$$xI_{irv}^t \geq 0 \qquad \forall \mathrm{i} \in I, \forall \mathrm{r} \in R, \forall \mathrm{v} \in V, \forall t \in T$$

$$xR_{rmv}^t \geq 0 \qquad \forall r \in R, \forall \mathrm{m} \in M, \forall \mathrm{v} \in V, \forall t \in T$$

The objective function (1) is to maximize the network total profit. Revenue is obtained from product sales. Total profit is determined by deducting various costs from revenue. The costs are comprised of: fixed setup and operating costs at facilities (inspection centers and remanufacturing centers), disposal and inventory holding cost, cost for purchasing virgin producy, transportation costs and costs reated to carbon emissions (both due to facilities and tranprotation).

Constraint (2) is the flow balance constraint at collection centers which ensures flow between collection and inspection centers up to availabile supply of returns. Constraint (3) and constraint (4) are flow balance constraints for t = 1 and t = 2...T respectively, showing the relationship between the disposal and inventory quantities at inspection centers. Constraint (5) is a flow balance constraint at the remanufacturing center that indicates the relation between the amount of returns remanufactured and purchasing new products depending on demand. Constraint (6) implies that the products transported from remanufacturing centers to markets are no more than the demand. Constraints (7) and (8) put capacity restrictions at inspection centers and remanufacturing centers with the opening condition. Constraints (9) - (11) represents the number of vehicles used for shipping products between collection and inspection centers, inspection and remanufacturing centers, and remanufacturing center and market utilizing no more than the maximum capacity of vehicles. Constraints (12) and (13) assure that once a facility (inspection or remanufacturing) is installed at a location, it should be operated till the end of the planning horizon. Constraints (14) and (15) ensure that there is no installation of inspection or remanufacturing centers in the first period. Constraints (16) and (17) imply that no inventory kept at the initial and final period of the planning horizon. Lastly, the remaining constraints are domain restrictions.

5. Results

To establish the performance of developed MILP, a numerical investigation on an example problem derived from actual remanufacturer setting is preseted. It should be noted here that the primary focus of doing this exercise is to develop a good intuition for drivers of the cost-efficient green reverse supply chain. Since this study entertains the possibility of investing in carbon efficient technologies at inspection/remanufacturing centers as well as using carbon efficient vehicles, this analysis is relevant for firms interested in becoming green either for economic or regulatory reasons.

The proposed model is solved using Microsoft Visual studio 2010 ultimate integrated with IBM ILOG CPLEX 12.5 on Intel® Core(TM) i5-4570T, 2.90 GHz processor with 8 Gb RAM.

5.1. Numerical Illustrative Investigation

In this section, we present a numerical study for an India based battery remanufacturing company. The primary focus of the numerical example is to illustrate the model and then investigate various sensitivity analysis relationships. These relationships help develop an intuition for cost-efficient green reverse supply chain network design. For the parameters selection design, we have taken into account inputs from the illustrative case company and extant literature.

5.1.1. Input Parameters

The firm sells its products in five markets, as considered in the numerical example. The firm can establish collection centers at the point of sale to collect the used products over a planning horizon comprising five periods. Management is planning to set up inspection centers at five potential locations and remanufacturing centers at three potential locations for processing the used products. Management is planning to hire three types of vehicles with different fixed and variable costs, capacity and carbon emissions for carrying products between centers. Therefore management wants to know where to install and locate the centers to reduce the setup cost, transportation, and emission costs and which and how many vehicles to be selected to carry products between centers.

The selling price and purchase cost of the products are in Indian Rupees (INR) 100 per unit and INR 60 per unit, respectively. These values are constant through the planning horizon. The emissions cost for transporting the products from one center to another and at inspection, and remanufacturing centers are INR 4 per kg of CO_2[1]. The inventory held at the inspection center at the cost of INR10/unit/period and disposed at the cost of INR4/unit if needed.

Table 1 shows the demand in each market. The data regarding distances between two different centers are provided in Tables 2(a) and 2(b) respectively.

<< Insert Table 1>>

<< Insert Tables 2 (a) and 2 (b) >>

Various parameters such as yield, capacity restrictions and different costs are shown in Table 3. The installation cost of remanufacturing centers is always greater than the inspection centers as expected in practical scenarios. The centers using advanced technology are more carbon efficient, but their setup cost is high.

<< Insert Table 3 >>

The supply at collection centers depends on the percentage of returns (also known as return factor) collected from the previous periods and taken as a value between 0.4 and 1. The supply of returns that are collected at five collection centers from earlier demand shown in Table 4. There are no returns in the first period, and hence total demand is only met by new products in this initial period.

<< Insert Table 4 >>

For carrying products, from one center to another in the problem environment, the firm hired three types of vehicles with different fixed cost and variable cost, carbon footprints, and capacity (Table 5).

<< Insert Table 5 >>

5.1.2. ***Results***

To understand the impact of investing in carbon-efficient technologies, we have compared all

[1] Center for Science and Environment (http://www.cseindia.org/content/walk-talk-carbon-taxmr-finance-minister)

the findings with and without a carbon emissions cost. The time taken to solve the problem is 578 seconds, for the case with emission cost and 410 seconds for the case without emission cost.

The facility location decision at a particular site is based on the capacity of the center, set up cost and carbon emissions released at the facility. As shown in Table 6, significant change is observed in the location of centers, when carbon emissions cost is added to the model. The results indicate that inspection centers are installed at locations 2, 3 and 4 when carbon emissions cost is incorporated. The inspection centers are installed in sites 2 and 3 because they have low set up costs and high yields with the same capacity. It is interesting to note that inspection center 4 is preferred over inspection center 1, even though setup cost is relatively high for inspection center 4. This result occurs because the model prefers inspection centers with high-yield, a quality measure. When carbon emissions costs are considered, inspection centers are installed at locations 4 and 5 due to their carbon efficiency. To process remaining quantities, one more inspection center is installed at location 2, which has the highest yield among locations 1, 2, and 3. We observed that yield plays an important role along with carbon emissions costs in installing inspection centers at a particular location.

<< Insert Table 6 >>

Remanufacturing centers are installed at locations 1 and 2 when there are no carbon emissions costs integrated into the model. The remanufacturing center is installed at location 1 because of a low setup cost. It should be noted here that there is no yield factor associated with the remanufacturing center. All parameters for sites 2 and 3 are similar, so the remanufacturing center is installed at location 2 to minimize the total transportation cost. Intuitively, with the presence of carbon emissions costs in the model, the remanufacturing centers are installed at locations 2 and 3 because of low carbon emissions costs even though they have high setup costs (almost equal to 2 times the installation cost at location 1).

We also observed that all types of vehicles were selected to transfer products from one center to another center based on capacity and carbon emissions. For example, if a firm wants to move a quantity of 157 units from collection center 1 to inspection center 4, then it is better to use two type 2 vehicles instead of one type 3 vehicle because its transportation and emission costs are less.

In general, the inventory was kept when: i. There were excess returns; ii. Limited capacity in centers; and iii. In a situation when operation and transportation costs to reach the market were significantly higher (as the operating costs are time-varying or dynamic). The inventory quantity at inspection centers in various time periods is shown in Table 7. For example, the inventory quantity in period 2, at inspection center 2 is different in both cases with and without carbon emissions cost and equal to eighty and two respectively. In the case with carbon emissions costs, the minimum distance from inspection center 2 to the remanufacturing centers is 69 km and, transportation cost and emission cost are 3160 and 248 respectively for a quantity of 262 units. However, in the case without emissions costs, the minimum distance from inspection center 2 to remanufacturing centers is 48 km, and transportation cost is equal to 2900 for carrying 340 units. So, to reduce the transportation cost along with emission cost between centers, the products are kept as inventory and processed in the following periods. All remaining inventory is disposed at the end of the planning horizon.

<< Insert Table 7 >>

In this model, we did not promote the disposal of the products unless there is high inventory or no production existed in the succeeding period. The total disposal quantity in both cases with and without carbon emissions costs is 120 and 70, respectively. Suppose 50 products are kept as inventory with a cost of 500, and if a firm disposes them at the cost of 200, then a firm loses a total amount of 700. Suppose if a firm used them in the next period then the processing and transportation charges to reach markets are about 1900, and the selling price is equal to 5000, so the firm will get a profit of 3100. So, the firm should not promote disposing of used products until the final period.

The purchase quantity is the amount to purchase from outsourced subcontractors when the amount of supply cannot fulfill the demand. The purchase quantity at all remanufacturing centers in various periods in both cases is shown in Table 8. The purchase quantity at remanufacturing centers 2 and 3 is less in the case when carbon emissions costs are included because the firm is always trying to remanufacture as many returns as possible. However, in the case without carbon emissions costs, the purchase quantity at all remanufacturing centers is relatively similar.

<< Insert Table 8 >>

Table 9 presents the comparison of various cost components with and without emissions costs incorporated. It is interesting to note here that although direct emissions costs are realized in vehicle and centers, it also affects all costs. This result clearly indicates the need for investing in green technologies to reduce emissions and subsequently aid firm profitability.

<< Insert Table 9 >>

In the case, with carbon emissions costs included the installation cost is equal to 49500 when compared to a cost of 40000 in the case when carbon emissions costs are not included. The emissions costs at the inspection and remanufacturing centers are equal to 13994 and 5942, respectively. The total operations cost at the inspection and remanufacturing centers to perform testing, sorting and remanufacturing operations is 57046 and 58819 in cases with and without carbon emissions costs, respectively.

At inspection centers, the inventory is kept for further periods, and total inventory cost is equal to 1890 and 1730 in situations with and without carbon emissions costs included, respectively. If the demand is more than the supply, then it is fulfilled by: i. Inventory from the last period; ii. Remanufacturing products from returns; and iii. Purchasing new products. The total emission costs of vehicles for transporting products between collection and inspection centers, inspection and remanufacturing centers, and remanufacturing center and markets are 8941. The total profit gained by the firm is the total revenue minus the sum of all costs, which are 186337 and 235159 in cases with and without carbon emissions costs, respectively.

5.2. Sensitivity analysis

Next, the impact of various parameters including capacity level, purchase cost, disposal cost, inventory cost, and the yield on the model are observed by keeping the other parameters static in the scenarios; where scenario 1 is with emissions costs and scenario 2 does not include emissions costs, as presented below.

5.2.1. Capacity Level

To understand the effect of capacity on profit, 8 experiments are executed on networks with limited and unlimited capacity level (Table 10). For experiment 1, the inspection centers are installed at locations 2, 4 and 5 owing to low carbon emissions and high yield. The remanufacturing center is installed only at location 1 in experiment 2 even though it has higher carbon emissions, but it is compensated by the unlimited capacity. The inspection center is installed at location 4 with more yield and fewer carbon emissions in experiment 4. The capacity level of all remanufacturing centers is unlimited in experiment 5, and the remanufacturing centers are installed only at location 3, even though it has more setup cost, it is preferred due to lower carbon emissions and transportation cost. The inspection center is installed at location 4 with more yield and low carbon emissions. The remanufacturing center is located at location 1 due to low setup and transportation costs; although it has more carbon emissions in experiment 8 where the capacity level of all inspection and remanufacturing centers is unlimited. From Table 10, the remanufacturing center is installed at location 2 when there is a limited capacity level of remanufacturing centers. The inspection center is installed at location 4 in all experiments and scenarios due to more yield, low carbon emissions, and reduced transportation costs.

<< Insert Table 10 >>

5.2.2. Purchase cost

The purchase cost was varied from 10 to 60 per unit, and the profit values are observed in both cases. From figure 2, we observe that there is an exponential relationship between profit and purchase costs in both the cases. Also, the deviation between profits in both cases widens as the purchase cost increases. That is, as the purchase cost increases, usage of the returned products also increased, which led to lessened inventories and disposal. For example, there is no remanufacturing completed up to a purchase cost of 28 per unit without emissions costs and 35 per unit with emissions costs included. Thus, all returns were disposed and with all demand being fulfilled by new products.

<< Insert Figure 2 >>

5.2.3. Disposal cost

The disposal cost is the expense attributed to the disposal of an unused return at the inspection center. The profit values as a result of varying the disposal cost from 2 per unit to 10 per unit product are observed. From Figure 3(a), we observe that, in the scenario of without emission cost, if the disposal cost is increased by a value of 2 per unit then the profit decreases at an average value of 140. However, the profit reduces by an average value of 240 in the scenario with emission cost up to disposal cost of 8 per unit, but further increase in disposal cost led to lessened marginal decreases in the profit value and shown in figure 3(b).

<< Insert Figure 3(a) & 3(b) >>

5.2.4. Inventory Cost

Inventory cost is the cost for holding returns at inspection centers for use in later periods as required. The impact of an increase in inventory cost (from 6 per unit to 12 per unit at an increment by 2 per unit) on profit values was studied. It is observed that if the inventory cost is low, then there is the likelihood of keeping more inventories at inspection centers. This means inventory quantity held at inspection centers will decrease with inventory cost increases, as expected. However, when inventory is stored because of limited remanufacturing centers capacity, then a decrease in profit is observed with inventory cost increases.

In the scenario with carbon emissions costs included, the profit value reduces linearly up to inventory costs of 12 per unit and later there is a lesser impact on the profit as shown in Figure 4(b). From Figure 4(a), it observed that, the profit value decreases almost linearly as inventory cost increases, when emissions costs are not included in the model. This result occurs because as inventory cost increases the inventory quantity decreases but the processing and transportation cost of those returned products increases which leads to a reduction in profit values and hence the almost linear behavior.

<< Insert Figure 4(a) &4(b) >>

5.2.5. Yield

In our model, the yield corresponds to the percentage of useful returns after inspection. To study the impact of yield, we tested the model with fixed values of high (0.8), medium (0.65), low (0.4) yield values and mixed yield values (i.e., different yields across different inspection-centers) and their subsequent effect on profit values. We observed that the profit with mixed yield is almost the same when compared to the profit at high yields; in both cases with and without emissions costs. This result can be attributed to inspection centers with higher yield values being preferred if other parameters are kept constant.

The tradeoff between yield and profit in both cases without and with emissions costs is shown in Figure 5(a) and Figure 5(b) respectively. From these figures, we infer that, as the yield is increased, the amount to remanufacture also increases which leads to a decrease in purchase quantity. The remanufactured products fulfil most of the demand in higher yield situations, and hence profit increases. A logarithmic relationship between yield and profit values was found to exist in both scenarios.

<< Insert Figure 5(a) &5(b) >>

To further understand the dynamics of the of the parameter setting, we plotted individual costs and decisions within the model with perturbations in each cost parameter. We provide these results in Appendix for better understanding of readers.

In this study, the carbon emissions from transportation are calculated on the basis of inter-facility distances. Since, collection centers (same as markets) do not include any inspection or remanufacturing activities, the CO_2 emissions at collection centers are not considered. Increasing the supply of returns will increase both the carbon emissions and transportation and operation costs but the usage of raw materials and decrease the wastage of the products; affecting environmental performance.

5.3. Multi-objective Solution

The ultimate aim of single objective optimization is to determine the “best” solution that minimizes or maximizes single objective function value which integrates all different objectives into one. This type of optimization is used as it provides decision-makers with a point solutions and insights into the nature of the problem. However, it provides only a single optimal solution. In contrast, a multi-objective optimization is used when the problem consists more than one conflicting objectives. It provides a set of alternative non-dominated solutions that trade-off both objectives. The proposed model uses ‘carbon emissions’ as the primary performance measure along with 'total cost'. It is a general practice to see how a point solution behaves on Pareto front of conflicting objectives. Towards this, we restructured our problem as multi objective problem and solved it using weighted average method.

Objective Function:

i. Maximize Total Profit

$$
\begin{aligned}
Maximize\ Z_1 = {} & p\sum_{r\in R}\sum_{m\in M}\sum_{v\in V}\sum_{t\in T} xR^t_{rmv} - \left(\sum_{t\in T}\left[\sum_{i\in I} SCI_i\left(y^t_i - y^{t-1}_i\right) + \sum_{r\in R} SCR_r\left(z^t_r - z^{t-1}_r\right)\right]\right. \\
& + \sum_{t\in T}\sum_{v\in V}\left[\sum_{c\in C}\sum_{i\in I} OCI^t_i xC^t_{civ} + \sum_{i\in I}\sum_{r\in R} OCR^t_r xI^t_{irv}\right] + \sum_{t\in T}\sum_{i\in I} DQ^t_i DC + \sum_{t\in T}\sum_{i\in I} IQ^t_i IC + \sum_{t\in T}\sum_{r\in R} BQ^t_r BC \\
& + \sum_{t\in T}\sum_{v\in V}\left[\sum_{c\in C}\sum_{i\in I} NC^t_{civ}\left(FTC_v + VTC_v dC_{ci}\right) + \sum_{i\in I}\sum_{r\in R} NI^t_{irv}\left(FTC_v + VTC_v dI_{ir}\right)\right. \\
& \left.\left. + \sum_{r\in R}\sum_{m\in M} NR^t_{rmv}\left(FTC_v + VTC_v dR_{rm}\right)\right]\right) \qquad (1.a)
\end{aligned}
$$

ii. Minimize Carbon emissions

$$
\begin{aligned}
Minimize\ Z_2 = {} & \sum_{t\in T}\sum_{v\in V}\left(\sum_{c\in C}\sum_{i\in I} dC_{ci} NC^t_{civ} E_v + \sum_{i\in I}\sum_{r\in R} dI_{ir} NI^t_{irv} E_v + \sum_{r\in R}\sum_{m\in M} dR_{rm} NR^t_{rmv} E_v\right) \\
& + \sum_{t\in T}\sum_{v\in V}\left(\sum_{c\in C}\sum_{i\in I} EI_i xC^t_{civ} + \sum_{i\in I}\sum_{r\in R} ER_r xI^t_{irv}\right) \qquad (1.b)
\end{aligned}
$$

As two objectives are linear, we formulated the problem as a weighted sum of the two linear objectives as follows.

$$Maximize\ Z = w_1 Z_1 + w_2 Z_2$$

Subject to Constraints 2 – 19

and $w_1 + w_2 = 1$

We solved this problem using CPLEX and Figure 6 shows a tradeoff between profit and carbon emission costs. We transformed carbon emission into a cost by assuming a carbon tax policy of INR 4 per kg of CO_2.

<< Insert Figure 6 >>

In the single objective solution, the total profit without carbon emission cost is INR 215214 and carbon emission cost is INR 28876. We see that the single objective model is providing overall best solution among all alternative solutions given by the multi-objective model.

5.4. Discussion

It is generally expected that lower emissions lead to higher costs and our analysis revealed the same. This internalization of externalities into the operations of systems provides a truer view of the environmental and social costs of doing business. The analysis also shows that moderate carbon taxes are sufficient to reduce emissions significantly. For example from table 9, we can see that a 60% difference in profit is due to emission costs.

Multi-tier supply chain activity solution sensitivities to relatively modest emissions costs changes should be carefully considered by managers and policymakers. Managers anticipating new carbon emissions rules and regulations should consider how quickly they can redesign their systems to respond to emergent policies. The timing of such revisions becomes even more critical if profitability is to be optimized. Some organizations may be able to prepare for regulatory eventualities related such environmental taxes or trading markets by preemptively incorporating these costs into their management policy. There are benefits and risks associated with such changes. Benefits may include having an initial first-mover advantage over competitors; where learning and acceptance of management become critical for successful and efficient implementation of new designs and operational policies. A major disadvantage may result from delays in policies or regulations, that may never be forthcoming and profitability of firms being affected.

6. Conclusion

In this paper, we present a mixed integer linear programming (MILP) model to solve a multi-tier multi-period green RL network including vehicle type selection. The paper contributes to the formulation and testing of the green RL model, which encompasses the vehicle type selection problem while considering the carbon emissions environmental effects.

The proposed model has several practical implications. Namely, product returns are collected in subsequent periods with some return rate in every period. Various kind of costs and parameters, values were set according to standard followed by industry and extant literature. The decisions made here were regarding the optimal selection of the sites for installation of inspection and remanufacturing centers, the product quantity that to be transported by which vehicle mode, how many vehicles to be used, the amount of quantity to purchase, dispose or store in inventory. Fewer potential locations for center installations mean that the distance between centers is greater with fewer possible routes. Thus, greater carbon emissions are leading to decreases in total profit and an increase in carbon emissions and transportation cost. Increasing the capacity and also the amount of used products results in reduction of carbon emissions and thus increase in total profit of the firm.

This model and study provides a number of improvements and extensions on previous remanufacturing network designs, but it has limitations and can be improved in a number of ways. The model can be extended to a multi-product scenario at the component level. The model can also be extended to take into account the other decisions on capacity. Our model can easily be extended to account for capacity decisions such as invest, stay or disinvest to increase or decrease capacities at new inspection or remanufacturing Center. The model only considered one environmental dimension, carbon emissions. Localized and other polluting elements, including other air emissions such as NO_x and SO_x, can be integrated. The multi-tier processes in this network are also simplified, although realistic based on case company considerations. More complex networks with variations in a variety of parameters make the model even more complicated. Helping to identify heuristics and solutions taking advantage of the structure of the model may be an important algorithmic solution, although the model is currently solvable using commercial software.

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Tables

Table 1: Demand Data

Market	1	2	3	4	5	Total
Period 1	346	310	270	203	328	1457
Period 2	174	345	188	277	267	1251
Period 3	322	284	259	196	172	1233
Period 4	270	325	300	333	232	1460
Period 5	237	225	347	193	158	1160

Table 2(a): Distance Matrix between Collection (C) and Inspection (I) Centers

	I1	I2	I3	I4	I5
C1	30	40	33	23	40
C2	40	45	35	41	33
C3	39	45	42	23	48
C4	31	39	21	22	36
C5	28	24	43	46	25

Table 2(b): Distance Matrix from I to Remanufacturing center (R) and R to Market (M)

I1	I2	I3	I4	I5		M1	M2	M3	M4	M5
76	48	63	66	47	**R1**	54	55	32	61	69
53	86	51	87	64	**R2**	69	62	49	43	66
64	69	85	87	71	**R3**	47	58	51	63	67

Table 3: Parameter values at centers

Parameters		Inspection Centers					Reman Centers		
		1	2	3	4	5	1	2	3
Setup Cost		3500	3500	3500	6000	6000	10000	17000	17000
Carbon Footprint		3	3	3	0.5	0.5	3	0.5	0.5
Max. Capacity		400	400	400	400	400	400	400	400
Yield		0.51	0.95	0.63	0.85	0.75			
	Period								
Operating Cost	**1**	6	5	5	8	6	10	12	11
	2	5	7	8	6	8	10	11	12
	3	7	7	5	6	8	12	10	11
	4	8	5	6	6	5	11	12	10
	5	5	8	6	7	6	12	11	10

Table 4: Supply of Returns

	Collection Center						
	1	**2**	**3**	**4**	**5**	**Total**	**% of Previous Demand**
Period 2	235	223	243	122	282	1105	0.76
Period 3	151	186	133	122	168	761	0.61
Period 4	180	227	124	118	134	784	0.64
Period 5	186	283	273	190	162	1094	0.75

Table 5: Vehicles data

Vehicle Type	1	2	3
Fixed Transport Cost	100	120	200
Var Transport Cost	10	12	20
Carbon Footprint	0.25	0.30	0.45
Max. Capacity	60	80	150

Table 6: Setting up of centers

Center	With Emission Cost	Without Emission Cost
Inspection Centers	2, 4, 5	2, 3, 4
Reman Centers	2, 3	1, 2

Table 7: Inventory Quantity

Period	With Emission cost		Without Emission cost	
	I Center	**Inventory**	**I Center**	**Inventory**
2	2	80	2	2
2	4	52	3	68
2	5	28	4	48
3	4	29	4	55

Table 8: Purchase Quantity

Period		Purchase Quantity	
		Without Emission cost	With Emission cost
	R1	580	580
1	R2	531	531
	R3	346	346
	R1	133	398
2	R2	164	47
	R3	174	26
	R1	163	409
3	R2	0	8
	R3	322	76
	R1	245	625
4	R2	185	119
	R3	270	62
	R1	97	347
5	R2	26	16
	R3	237	0

Table 9: Various price/costs comparison with/out carbon emission costs

Parameter	Without Emission cost	With Emission cost
Selling price	656100	656100
Setup cost	40000	49500
Operation cost	58819	57046
Inventory cost	1730	1890
Disposal cost	280	480
Purchase cost	208380	215400
Transportation cost	111732	116570
Emission cost - Vehicle	Not Considered	8941
Emission cost - Centers	Not Considered	19936
Total Profit	**235159**	**186337**

Table 10: Effect of Capacity on Network

S.No	Capacity Level				Opening of I Centers					Opening of R Centers			Profit
	Inspection Centers		Remanufacturing centers		Carbon Inefficient			Carbon efficient		Carbon Inefficient	Carbon efficient		
	Carbon Inefficient	Carbon efficient	Carbon Inefficient	Carbon efficient	1	2	3	4	5	1	2	3	
1	UL	L	L	L	N	Y	N	Y	Y	N	Y	Y	187280
2	L	L	UL	L	N	Y	N	Y	Y	Y	N	N	195474
3	UL	L	UL	L	N	Y	N	Y	Y	Y	N	N	195474
4	UL	UL	L	L	N	N	N	Y	N	N	Y	Y	198658
5	L	L	UL	UL	N	Y	N	Y	Y	N	N	Y	209035
6	UL	UL	UL	L	N	N	N	Y	N	Y	N	N	207715
7	UL	L	UL	UL	N	Y	N	Y	Y	N	N	Y	209035
8	UL	UL	UL	UL	N	N	N	Y	N	Y	N	N	222658

Y – Opened N – Not opened UL – Unlimited L – Limited

Figures

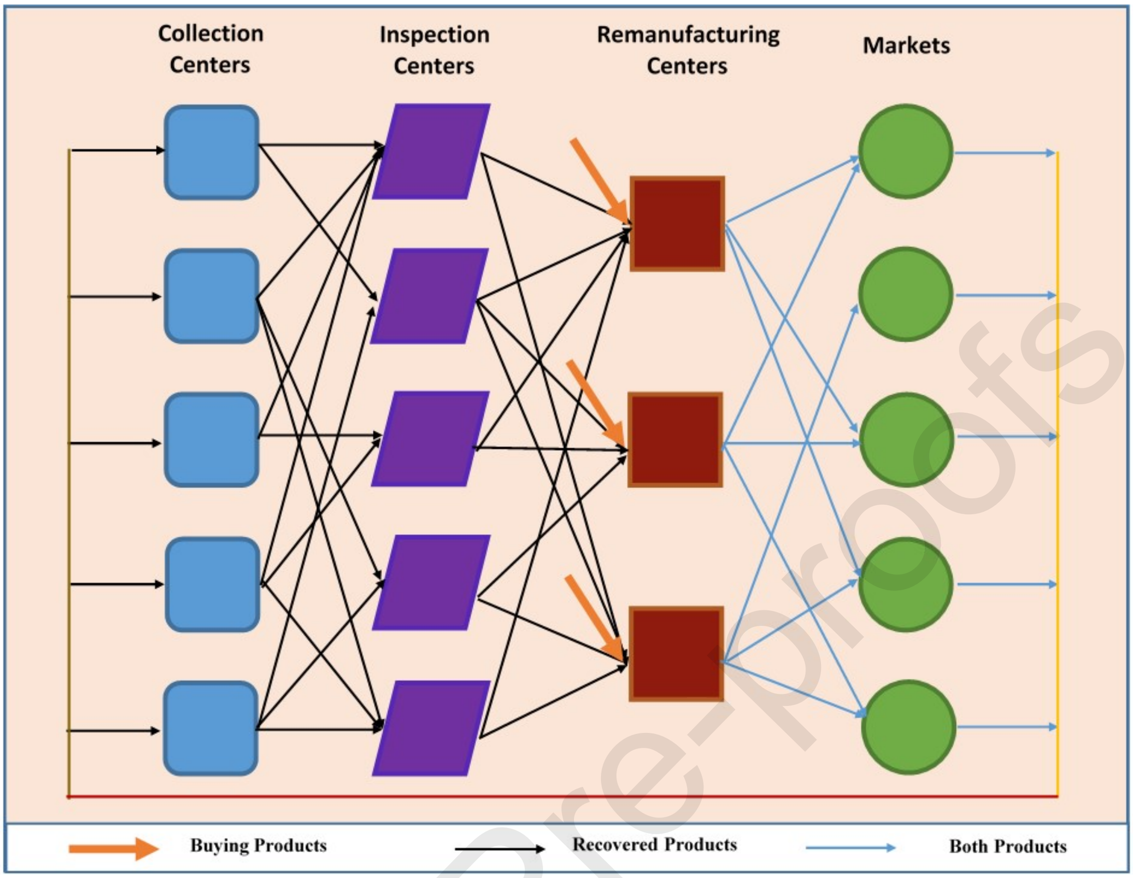

Figure 1: Green reverse supply chain network

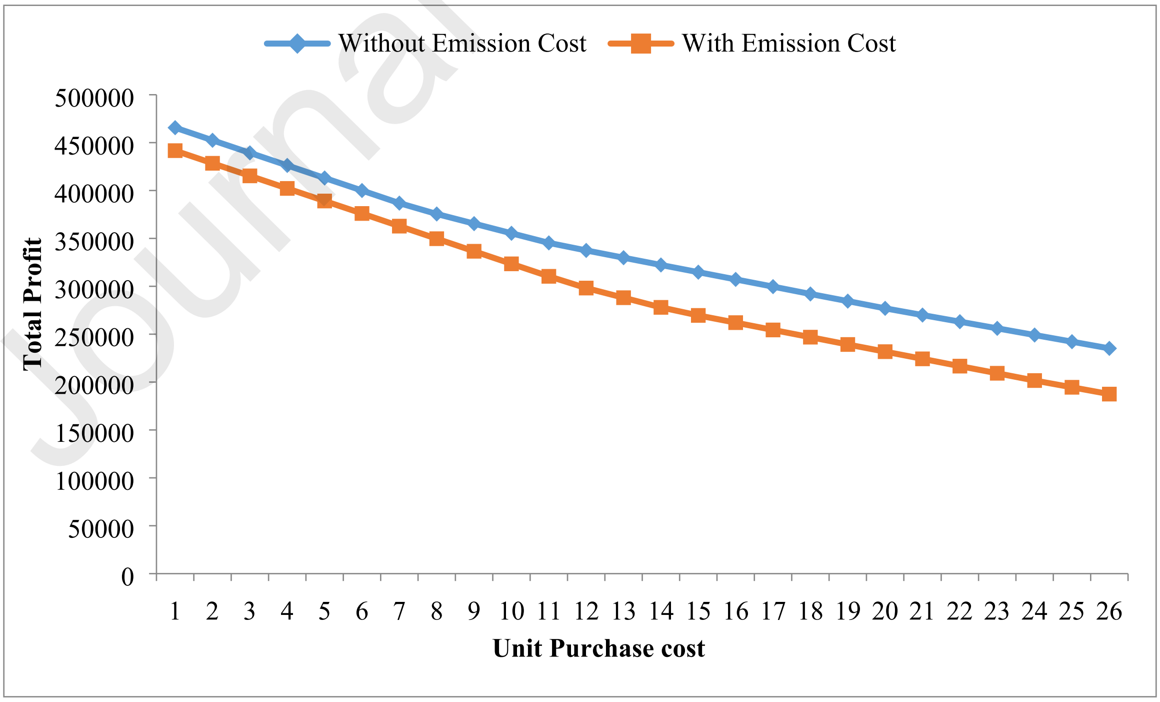

Figure 2: Tradeoff between purchase cost and profit

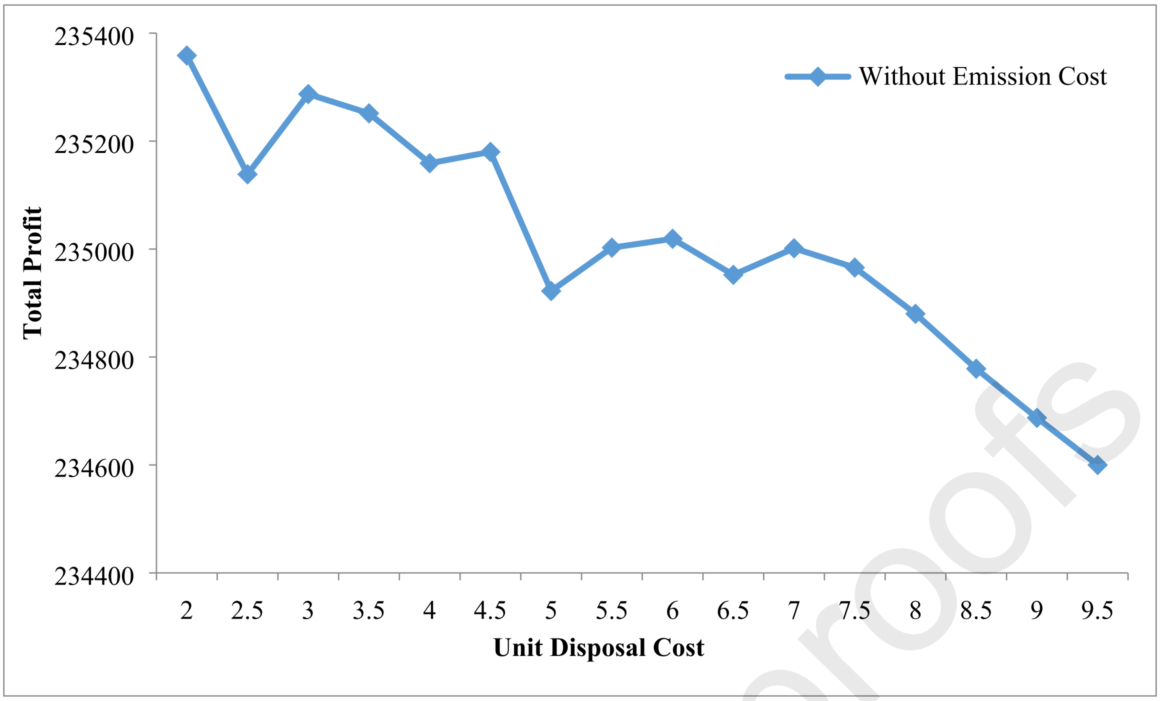

Figure 3 (a): Tradeoff between disposal cost and profit – without emission cost

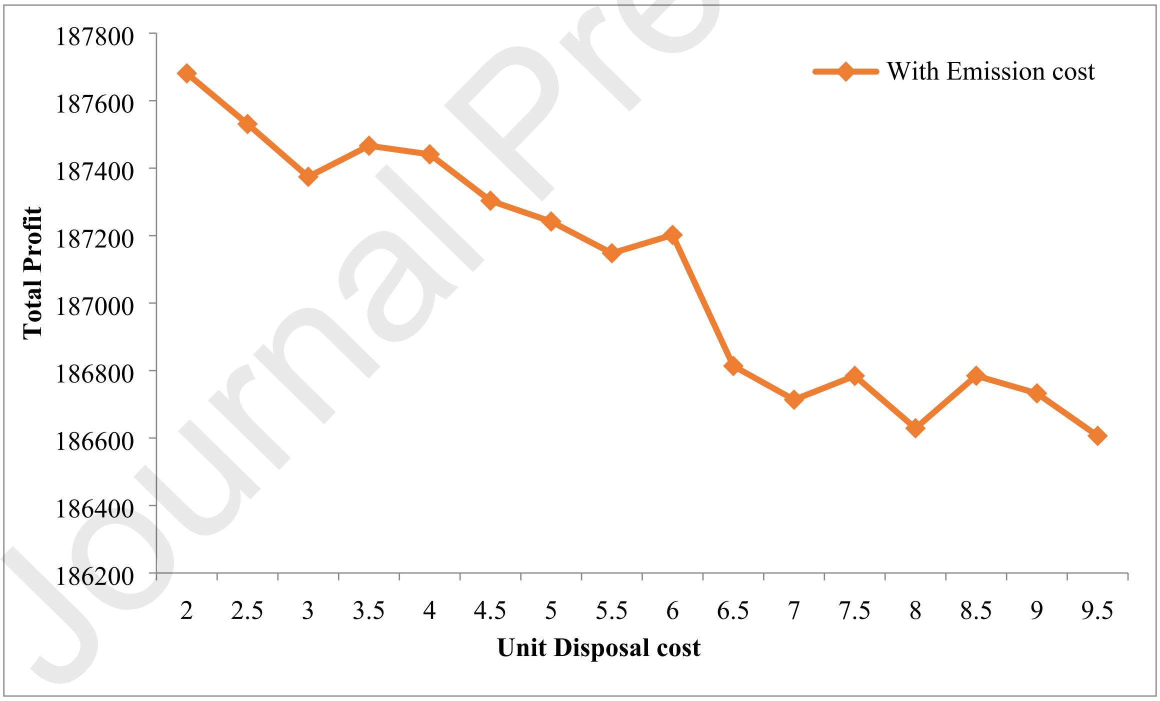

Figure 3 (b): Tradeoff between disposal cost and profit – with emission cost

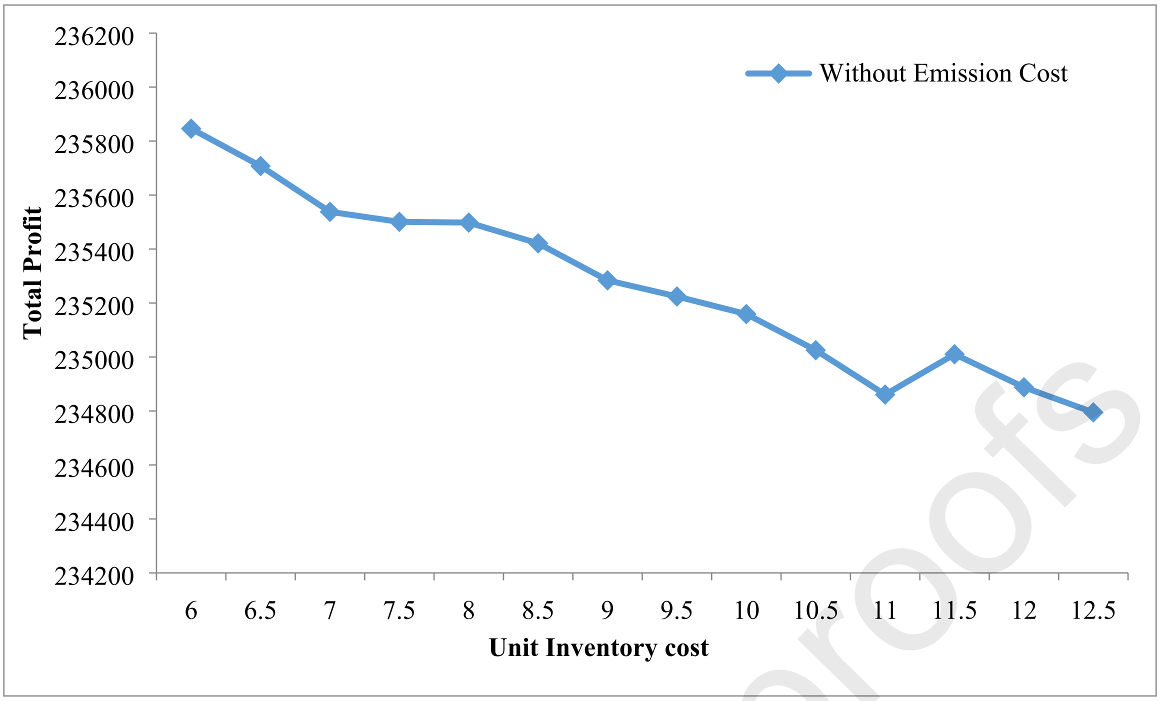

Figure 4 (a): Tradeoff between inventory cost and profit – without emission cost

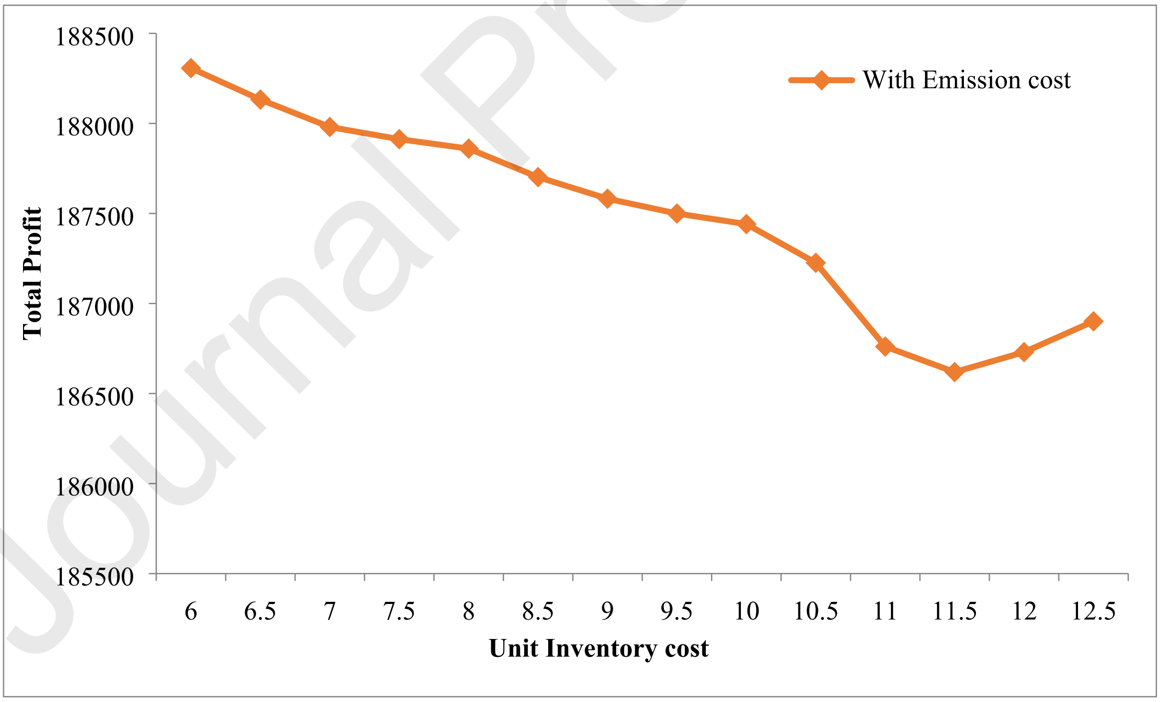

Figure 4 (b): Tradeoff between inventory cost and profit – with emission cost

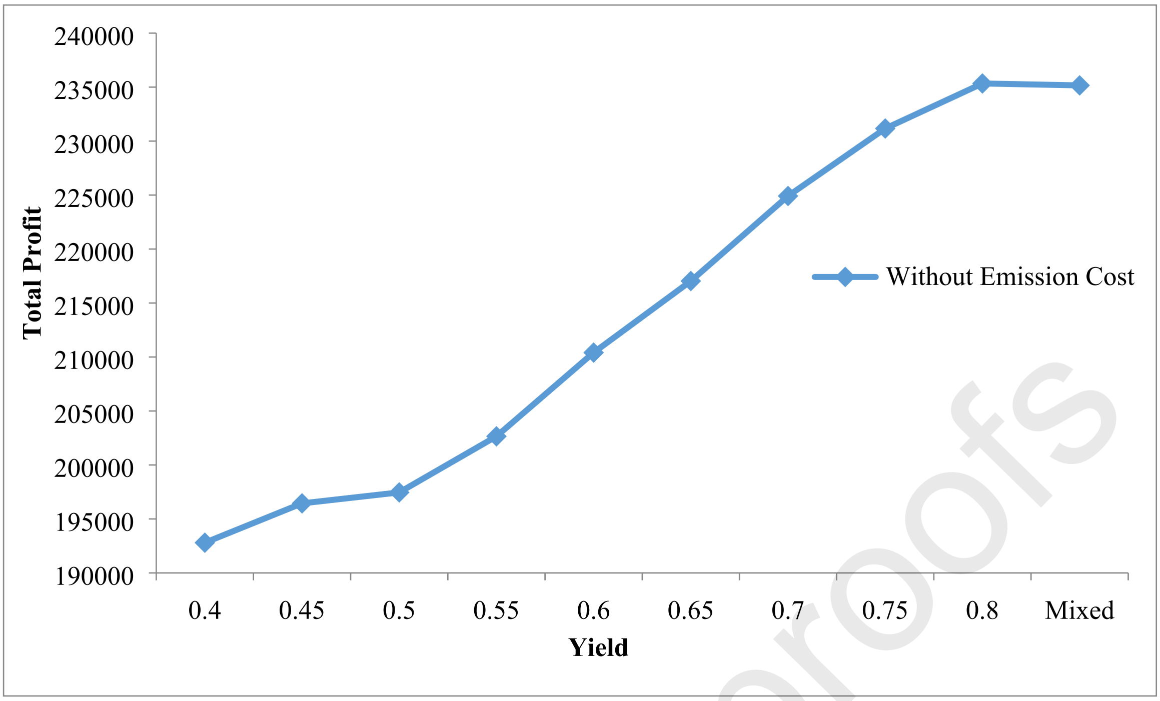

Figure 5 (a): Tradeoff between yield and profit – without emission cost

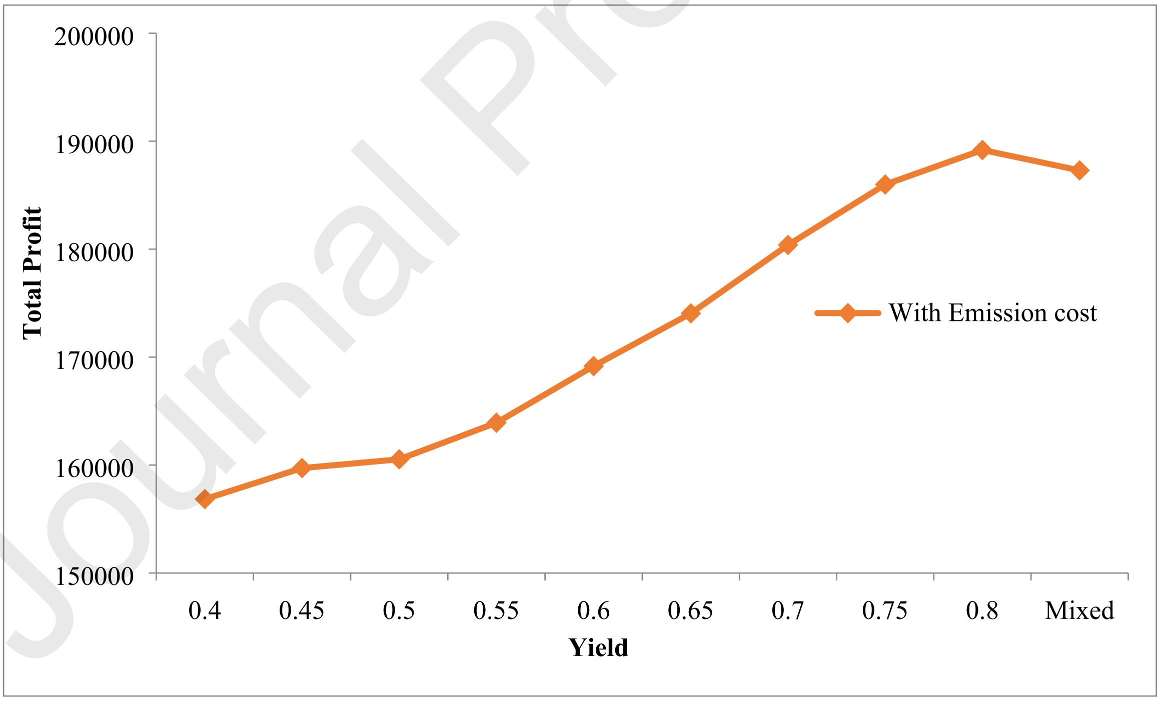

Figure 5 (b): Tradeoff between yield and profit – with emission cost

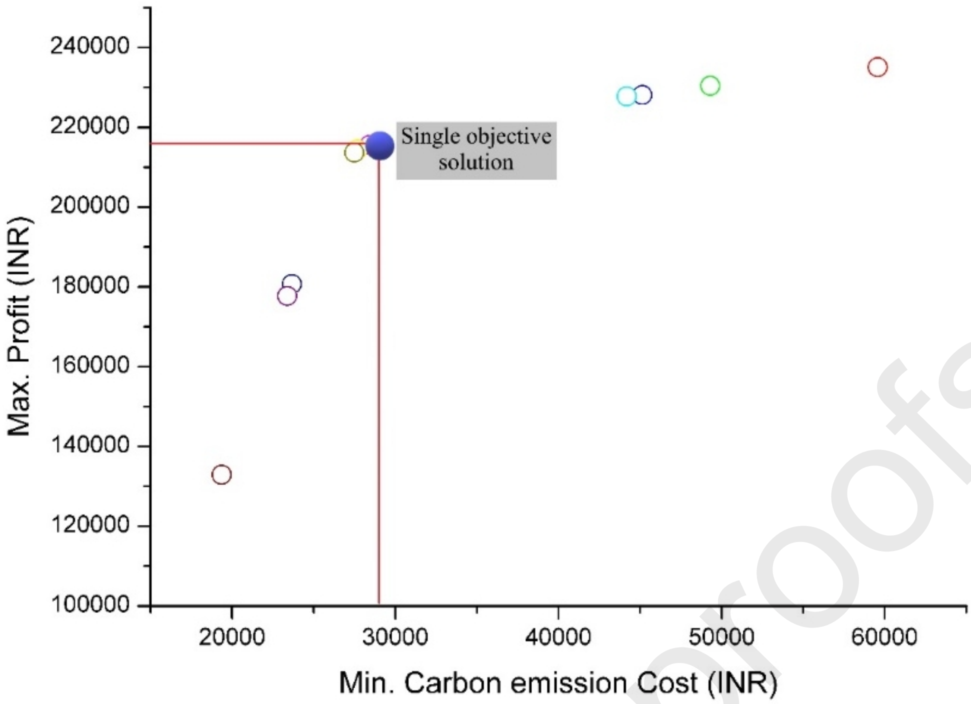

Figure 6: Tradeoff between carbon emissions (as cost) and profit

Highlights

1. Effective and practical framework for green reverse logistics network design.
2. A multi-period MILP model accounting locations, transportation, remanufacturing.
3. Accounted carbon emissions from facilities and transportation.
4. The effect of carbon tax on optimal decisions is presented.
5. Sensitivity of optimal decisions with respect to problem parameters is analysed.