Planning Environmental and Economic Sustainability in Closed-Loop Supply Chains

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ABSTRACT
A closed-loop supply chain model that incorporates environmental and economic sustainability issues into the planning process of a chain is proposed. End-of-use and end-of-life customer returns are collected through retailers and supply chain-operated collection centers (SCOCs), which are located between the retail outlets that are separated with a distance exceeding a set limit, to facilitate customer returns. Returns are dismantled into components, which are recovered through recovery service providing vendors (RSPs). As much as possible, recovered components are used to produce remanufactured products through quality enhancement. The remaining recovered components are then used to produce second-hand products. The proposed model integrates the overall operations costs and select life cycle assessment (LCA) metrics in procurement, production, collection of returns, recovery, reuse, remanufacturing, transportation, and distribution of products to attain environmental and economic sustainability. Numerical examples illustrate the model's applicability.

Keywords: environmental and economic sustainability, closed-loop supply chain, collection of returns, LCA metrics, component recovery, remanufacturing, a mathematical model

1. INTRODUCTION
Closed-loop supply chain practices have been increasing in the USA and globally in recent years. This increase is evidenced by the 15% (reaching at least up to the US $ 43b) growth of US remanufactured products as reported in United States International Trade Commission (2012). Such growth is also supported by the findings of a report by Global Industry Analysts (2015) that indicated the rapid growth of automotive parts remanufacturing. As there is no unique definition of sustainability (Szolnoki, 2013), most of the research uses the definition of sustainable development by the World Commission on Environment and Development (1987, the Brundtland Commission): “Sustainable development … meets the needs of the present without compromising the ability of future generations to meet their own needs.” Thus, supply chains (SCs) should pursue sustainable development to prevent the negative environmental effects that typically characterize current business practices (Abdallah et al., 2012).

There are three basic sustainability requirements: social, economic, and environmental. Economic and environmental sustainability challenges can be used to shape business planning, which indirectly addresses some of the social sustainability issues. Business must learn to integrate sustainability considerations into their business processes, as customers are increasingly imparting the highest importance to sustainability requirements (Berns et al., 2009). Following Guide and Van Wassenhove (2009), a closed-loop SC (CLSC) collects end-of-use and end-of-life customer returns; recovers products and/or the sub-assemblies, modules, and components from the returns; and reuses them to produce remanufactured and second-hand products of different quality levels.

CLSCs increase products’ useful life while reducing resource wastage to address sustainability issues. CLSC with a focus on remanufacturing results in saving natural resources, energy, dumping/fill space, clear water and air in addition to supporting economic sustainability (Bhattacharya et al., 2018). They also improve firms’ economic sustainability by increasing revenue, market shares, and customer satisfaction through creating product choices and by offering products at a variety of quality levels for a reduced price. CLSCs indirectly serve social sustainability by creating more jobs and job types in recovery services and driving a social urge for appropriate product designs that facilitate quick dismantling and recovery.

Today, SCs emphasizes the core areas of their businesses and supplement the non-core areas through supply management or third-party logistics (3PL) to improve their financial performances. Hence, establishing a sustainable supply management process for the forward SC to have high-quality parts for new products and RSPs for reverse SC process to have appropriate quality recovered components/ modules at competitive cost are advantageous options for involving suppliers and 3PLs for further enhancing competitiveness in CLSC. SCs can further improve their sustainability by including the selection of green supply management for CLSC process and manufacturing and remanufacturing practices in addition to using quality assurance-based supplier affiliations that make it possible to forgo inspection, obtaining timely supply to reduce inventory levels and reducing packaging costs (EPA, 2000).

Under green manufacturing practices, SCs have the option to implement quality metrics-based plant capability evaluation procedures. These allow them to allocate production exclusively to quality capable plants and capable RSPs to prevent scrap generation, maintain optimal performance and ensure safety. Plants’ high processing capabilities also influence customers’ confidence in organizations. Such quality assurance improves manufacturing resiliency and the related practices contribute to economic sustainability by improving the overall SC resiliency level. This is achieved by including capacity,
supply, and recovery services flexibility addition to improving plant reliability and thus processing capability. CLSCs with quality assurance-based supply and manufacturing management integrate resilience creation by maintaining high processing capability and including supply and capacity flexibility to achieve environmental and economic sustainability.

Table 1 Highlights of contributing factors of this research compared to Literature

| Articles                  | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| This research             | √   | √   | c),d),f | √   | √   | √   | √   | √   | √   |
| Bhattacharya et al. (2018)| a)  | √   | √   | e)  | X   | X   | X   | X   | X   |
| Bhattacharjee and Cruz (2015)| a) | √   | √   | d), e) | X   | X   | X   | X   | X   |
| Ovchinnikov et al. (2014)| a)  | √   | X   | X   | X   | X   | X   | √   | X   |
| Atasu and Cetinkaya (2006)| a)  | √   | X   | d), e) | X   | X   | X   | √   | X   |
| Abdallah et al. (2012)   | a)  | √   | X   | d), e) | X   | X   | X   | √   | X   |
| Han et al. (2017)        | a)  | X   | X   | c), d), e) | X   | X   | X   | X   | X   |
| Hasnov et al. (2019)     | a)  | √   | X   | e)  | X   | X   | X   | √   | X   |
| Kalverkamp and Young (2019)| b) | √   | X   | d), e) | X   | X   | X   | X   | X   |

Factors: (1): Research method: a) Modeling based (this research is model based), b) Empirical; (2) Remanufactured product; in this research t=2 represents remanufactured product in the model variable y_{ptkr} defining distribution of product in model equation (2), and variable x_{ptjk} defining production of product in model equation (3.a); (3) Second hand product; in this research t=3 represents second hand product in the model variable y_{ptkr} and x_{ptjk}; (4) Collection of returnable by c) Retailer; variable r_{fpr} defines collection of returnable by retailer in the model equation (3.b); d) SC operated collection center; variable r_{pc} defines collection of returnable by SC operated outlets in model equation (3.b); e) Collection by vendor by f) Offering incentives; paid by retailer and included in their service charge in the model parameter CRC_{pr}; and paid by SC operated outlets and is included in their collection cost in model parameter CP_{pc}; (5) QA affiliated supplier in this research model parameter qa, in constraint (23) ensures such affiliation, RSP, to reduce inventory, timely supply, 0 rejection, and forgo receiving inspection; (6) Production in QA-capable plants in this research Model parameter qc, in constraint (24) ensures such determination; (7) Supplier and plant capacity flexibility to improve resilience; in the proposed research model constraints (25) and (26) ensure such flexibility; (8) Ecological factors—minimize energy use, harmful emission; (9) Including SC operated collection center through the model variable p_{mcrr1} in between retailers to improve product returns, thus improve environmental sustainability and customer service in turn economic sustainability. ‘X’ means not addressed; ‘√’ considered.

Figure 1 Schematic flows of product and various entities of proposed CLSC
This research contributes to the literature by proposing a CLSC model that integrates flexible collection and recovery processes, flexible supply, recovery and capacity allocation, remanufacturing, the manufacture of second-hand and new products and quality metrics-based plant allocation to achieve environmental and economic sustainability. Distinguishing contribution of this research compared to extant literature are briefly described in Table 1.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature; Section 3 presents the problem statement and formulates the model; Section 4 illustrates the applicability of the model and the approach using numerical examples; and Section 5 provides a discussion and concludes the study. Figure 1 shows schematic flows of product, process and various entities in the proposed CLSC.

2. LITERATURE REVIEW

Design issues for CLSCs and the design of sustainable SCs are the two streams of research that created the background for this research. Since most of the research includes CLSC and sustainability factors in a combined way, our review study does not show the streams separately.

It is increasingly common for progressive companies to adopt sustainability practices in their business operations, perhaps in response to the expectations of academia and society regarding the importance of implementing sustainable practices, seeking renewable resources and controlling harmful emissions (Martin and Kemper, 2012). It is now almost established that becoming environmentally friendly in company operations lower costs and improve revenues (Nidumolu et al., 2009). Green SC practices, which integrate environmental management into SCs’ overall business operations, have been found to improve both environmental and economic performance. One of the approaches for implementing green SC management is product recovery through the formation of a CLSC (Abdallah et al., 2012).

Product recovery reuses end-of-use and end-of-life products rather than discarding them, and includes value-added recovery in the form of remanufacturing, repairing and refurbishing. The recovery and reuse of components, products, and modules contribute to energy savings for the overall SC process, and resource conservation. As such, it addresses environmental sustainability by reducing the requirements of virgin materials, energy consumption, and landfill space. It also improves businesses’ economic sustainability by increasing SCs’ profits and profitability (Guide et al., 2003). Remanufacturing, in general has been found to have a positive effect on organizations’ economic sustainability performance. Using a data-driven analysis based on the practical industry data for cell phones, Ovchinikov et al. (2014) concluded that remanufacturing supports economic sustainability goals by increasing profit and promotes environmental sustainability goals by reducing overall energy consumption in most situations. In the cases of demand growth, they revealed that a firm’s energy consumption may increase. The study of Bhattacharya et al. (2018) considered remanufacturing with the main motivation of improving the economic performance of a CLSC organization that is involved in manufacturing and remanufacturing of mechanical type products. The organization themselves collects the end of life/ used products and conducts repair/refurbishment steps for the components/products and sells them with the new product. In the reverse loop, the CLSC pays higher acquisition costs for good quality returned products, which remain lower than the new components. Bhattacharyya et al. studied a multistage non-linear modeling-based approach for optimum pricing of the product and thus to improve the economic performance of the CLSC with remanufacturing. In a similar model-based CLSC with remanufacturing study Hasanov et al. (2019) optimized total SC cost. The study also considered emissions and energy consumption from production and transportation of products. The study reported that higher collection rates of used products for remanufacturing improve profit and environmental sustainability performance. The research considered minimum cost coordination of orders to suppliers, vendors for collection of used products and inventory level. The study did not consider quality and sustainability improvement systems/steps for supply and manufacturing management.

Remanufacturing may be considered an opportunity for improving the sustainability performance of a CLSC. Reimann et al. (2019) considered process innovation while designing CLSC for remanufacturing. The research developed a mathematical model to find out the benefits of investments in the Process Innovation for Remanufacturing (PIR) approach in a CLSC. Reimann et al. reported that a CLSC should invest aggressively to achieve benefits for lower unit costs. If the organization can not invest as needed for such innovation, it should not go for PIR. They considered collection, recovery and remanufacturing by retailers and manufacturers. The study mentioned that the manufacturer should be involved in collection, recovery and remanufacturing directly to understand what measures should be taken for PIR.

Bhattacharjee and Cruz (2015) proposed a model-based approach that provided decision-making criteria to CLSC participants for economic viability. The participants mentioned were the producers, RSPs, remanufacturers, recyclers, and consumers. The research considered economic viability as the key ingredient for sustainability. Using data from recyclers, markets, and the SC literature on consumer electronic products, the authors concluded that above-zero return rates for end-of-life return policies are important across all consumer types to ensure sustainable systems. Judicious return rates are necessary for creating balance in the market places, as they ensure the availability of refurbished products, which was reported by Bhattacharjee and Cruz to be crucial for CLSC sustainability. They also studied profitability and sustainability and reported that providing viable and sustainable return policies for the before-end-of-life and end-of-life returns increases sales for both customer types. However, their research is only applicable to consumer electronic goods with short product lifecycles.

The literature also covers the approaches for the collection of customer returns in addition to the recovery, manufacturing, and marketing of products of different quality types (remanufactured, second-hand and special) for the recovered components. Savaskan et al. (2004) studied the problems involved in the collection of customer returns through manufacturer-, third-party subcontractor- and
retailer-operated collection channels. In a decentralized environment, retailer-operated channels have proven most effective. Collection strategies and channels influence the time required for returns to flow through the remanufacturing and recovery processes. Time is crucial if there is an active demand period within a product’s lifecycle. Atasu and Cetinkaya (2006) studied collection and flow times in their analytical model to decide shipment intervals and quantities for optimal remanufacturing profitability. An appropriate incentive scheme can motivate products’ users to return them earlier in their lifecycles, and earlier returns result in better quality. It is also clear that such incentives can contribute to increased efficiency, quality and quantity of returns. Han et al. (2017) studied the production decisions by a CLSC with two collection channels that include retailer and SC’s channel. The study reported that without disruptions and sometimes with limited disruption, CLSC achieves more profit with the retailer collection channel. But with disruptions, SC’s channel is robust and does better. Here by disruption the authors meant remanufacturing cost-related disruption for various reasons. Han et al.’s study followed an analytic modeling-based approach for their study. The study did not consider the supply and manufacturing related aspects. For furthering sustainability through the reverse loop of SC, circular economy based approach, open loop - based approaches are studied in Kalverkamp and Young (2019). Using various case studies, they presented that an open loop-based approach may provide better sustainability. In their research closed-loop takes back the product for remanufacturing to OEMs. Through their study, they showed that a third party based (open loop) approach for collection, recovery and remanufacturing has the scope of innovation and better sustainability. The use of RSPs in our research is one of the components of future-looking open-loop approach in the circular economy.

Guide et al. (2000) proposed a market-driven strategy that relies on financial incentives to motivate end users to return the product earlier, thus ensuring better quality. CLSCs include steps to improve environmental and economic sustainability by limiting harmful emissions and spent energy from the overall SC process. Such steps may be part of complying with government regulations and/or exercising social responsibility. Based on a similar motivation, the Australian government implemented an emission trading scheme (ETS) that imposes a tax based on the generation of per ton of CO2 equivalent (Fahimnia et al., 2013) to limit harmful emissions. The Australian carbon ETS and European ETS (2005) are similar programs.

Selecting environmentally friendly product designs, manufacturing processes and materials can improve sustainability by reducing energy requirements, harmful emissions and waste disposal in lifecycle analysis frameworks. The selection of alternative designs studied by Krikke et al., (2004) and the production processes, components and raw materials examined by Dalquist and Gutowski (2004) represent some of the excellent literature in this area. Planning SC cargo transportation is one of the crucial areas in which sustainability can be improved in terms of reducing energy consumption and harmful emissions. In 2007, transportation accounted for 28.4% of US energy consumption and 33.6% of CO2 emissions. The amount of cargo shipped is expected to triple in the next 20 years. Forty-four Fortune 500 companies have addressed the environmental impacts of transportation by pursuing 11 practices, as described in the state-of-the-art research conducted by Golicic et al. (2010).

It is apparent that sustainability has become a key element in SC (Kleindorfer et al., 2005). Kleindorfer et al. observed that this sustainability requirement developed performance measures for businesses in terms of 3Ps (people, profit, and planet), created the goal of maintaining viable social franchises (trust of employees, customers, and communities), in addition to economic franchises. In effect, the state-of-the-art research by Kleindorfer et al. established crucial requirements of environmental and economic sustainability. Based on the literature review and their analysis Kleindorfer et al. (2005) mentioned CLSC to foster environmental and economic sustainability. Thus, the model-based approach for planning CLSCs (similar to our research) helps SC managers improve the environmental and economic sustainability of their businesses.

The literature includes a new business trend and research stream wherein companies are switching from narrow profit focus to a broader triple bottom line (people, profit and planet). Accordingly, to be sustainable, a business must be socially and environmentally responsible, just as profits are essential for business continuity (Besiou and van Wassenhove, 2015). This stream of research supports our approach by emphasizing economic (profit) and environmental (planet and people) sustainability through a triple bottom line focus.

Firms are currently emphasizing their core functions, depending on suppliers for components, subassemblies and, occasionally, for the entire product. In this situation, SCs’ sustainability performance is decided by the suppliers’ sustainable practices. According to Seuring and Muller (2008), the management of materials, information, and capital as they flow along the SC are shaped by the goals in all three sustainability dimensions (environmental, economic and social), which are derived from customer and stakeholder requirements. The literature is rich in the role of better supplier management in obtaining improved environmental performance (Bowen et al., 2001; Corbett and Klassen, 2006) and improved social and economic performance (Vachon and Klassen, 2006; Gimenez and Tachizawa, 2012).

The above literature review highlights and guides sustainability considerations in different SC operational functions. Our research includes a model-based approach to consider the sustainability practices suggested in the literature by extending and adding select cases, such as creation of supplier flexibility by assigning more than one supplier for an input and similarly production flexibility by allocating production of product to more than one plant for improving economic sustainability by reducing risk of supply and production failure.

3. METHODOLOGY - THE CLSC PLANNING MODEL

This section presents the problem statement, notations and mathematical model for CLSC planning. Schematic flows of product concerning various entities of this proposed model has been presented in Figure 1 at the end of Section 1. The proposed model will plan a similar CLSC process. As
discussed before considering several variables and factors involved in a CLSC planning process this research follows a mathematical model-based planning process for improving the economic and environmental sustainability performance of a business organization.

3.1 Problem Statement
A manufacturing-based business follows a CLSC process for producing and marketing a set of products $p \in P$. Based on a recent customer survey, the SC would like to enhance its reverse loop of CLSC operations to achieve optimum environmental and economic sustainability through a model-based approach. For achieving the objectives the CLSC model decides to manufacture $x_{pjk}$ product $p \in P$ of type $t$ ($t=1$ new, $2$ remanufactured and $3$ second-hand quality) in the plant $j \in J$ and transports them to the distribution centers (DCs) $k \in K$, and from the DC $k$ the model plans to distribute $y_{pjk}$ product $p \in P$ of type $t$ to retailers $r \in R$ located at various markets $m \in M$. Each market has independent retailers that are different from other markets. The SC has contracts with retailers to collect returns in exchange for a service charge for each equivalent product. In the reverse loop the CLSC model plans collection of customer returns through retailers $r \in R$ and SC’s collection centers (SCOC) $c \in C$ that are positioned in between retail outlets when the distances between the retail outlets exceed DSL, a distance limit set by the SC to facilitate customer returns by keeping the return options at a proximity of the customer. For opening a SCOC $c$ the CLSC model decides $p0_{mcrc} = 1$ when distance between retailer combinations $(r, r1)$ for a market $m$ exceeds a set distance DSL. New products ($t=1$) are made by procuring $z_{is}$ new components $i \in I$ from a pool of supplier $s \in S$ that are quality affiliated following the procedure in Das (2011); $n_{rs}$ also denotes the procurement of new component $i \in I$ from supplier $s \in S$ in special circumstances to compliment shortage of quality enhanced recovered component for realizing remanufactured product. Collection of customers returned products (defined as returns in this paper) by retailer $r \in R$ and SCOC $c \in C$ are influenced by incentive-based scenarios as created by providing incentive related information on the product labels. Highlights of scenarios for the incentive plan: the study estimated cost of production by considering the required raw materials and estimated processing cost of a standard product. Based on such cost the SC devised an incentive plan which is printed on the product label to motivate customers to return end of use product in a good condition. According to this plan, the customer is offered 75% to 80% of the product value if 100% of the components of the product are in good recoverable condition, 60% of the value if 70% of the components are in good condition, 40% of the value if 50% of the components are in good condition, and 25% of the value if 30 to 35% of the components may be estimated to be in good condition. The detail of incentive plan is illustrated in the numerical example to follow. The collected returns are then sent to a pool of RSPs $v \in V$ for sorting out the suitable product, dismantling the component, and recovery of usable components. Retailers and SCOCs send the returnable to RSPs, which are covered within the collection cost of returns. $rz_{iv}$ is the estimated amount of recovered component $i'$ that the SC procures from RSP $v$. These recovered components are used to realize remanufactured products after quality enhancement. The components that cannot be quality enhanced are used for the second-hand product, and a % of these become unusable. SC’s objective is to maximize profit by addressing targeted economic and environmental sustainability issues. Examples of such issues include reduction of emissions, energy consumption, reusing maximum possible % of components by including second-hand products which reduce wastes thus improves environmental sustainability and economic sustainability by including additional product variety (second-hand products) and, providing more choices of products to the market.

3.2 Notations

**Index:**
- $C$ : set of collection centers $c \in C$
- $E$ : set of scenarios for collection of returns $e \in E$
- $I$ : set of components (new) $i \in I$; $I'$ set of recovered components $i \in I'$
- $J$ : set of plants $j \in J$
- $K$ : set of distribution centers (DCs) $k \in K$
- $P$ : set of products (new/remanufactured) $p \in P$
- $R$ : set of retailers $r \in R$
- $S$ : set of component suppliers $s \in S$
- $T$ : product quality type $t \in T$, where $t = 1$ new, $t = 2$ remanufactured, and $t = 3$ recovered second-hand product
- $V$ : set of RSPs $v \in V$

**Decision variables:**
- $a_{ic}$ : 1 if collection center $c$ is opened, 0 otherwise
- $ak_{ir}$ : 1 if DC $k$ is allocated to supply retailer $r$, 0 otherwise
- $ar_{pv}$ : 1 if recovery of product $p$ is set up by RSP $v$; 0 otherwise
- $in_{pk}$ : inventory for keeping safety stock of product $p$ in DC $k$ to mitigate product shortage in market
- $n_{zis}$ : Specially procured component $i$ from the supplier $s$ to compliment shortage of recovered and quality enhanced components for remanufactured product
- $or_{r}$ : 1, if retailer $r$ is in a contract to collect returns, 0 otherwise
- $p0_{mcrc}$ : 1 if a collection channel $c$ is opened in market $m$ between retailer $r$ and $r1$, 0 otherwise
- $rc_{pc}$ : amount of product $p$ collected by the SCOC $c$
- $rp_{pv}$ : product $p$ received by RSP $v$
- $rr_{pr}$ : amount of product $p$ collected by retailer $r$
- $rz_{iv}$ : input $i$ recovered by RSP $v$
- $w_{ij}$ : 1 if production of product $p$ is set for producing in plant $j$, 0 otherwise
- $x_{pjk}$ : product $p$ of quality type $t$ manufactured in plant $j$ to transport to distribution center $k$
- $y_{pjk}$ : product $p$ of quality type $t$ distributed from DC $k$ to retailer $r$
\[ y_{itr} = \text{an auxiliary 0/1 decision variable to facilitate opening a SC’s own operated collection center between retailer } r \text{ and retailer } r' \]

\[ z_{is} = \text{input } i \text{ procured from supplier } s \text{ (new inputs/components)} \]

**Parameters:**

- \( \text{CAP}_{pj} \): capacity of producing product \( p \) in plant \( j \)
- \( \text{CAS}_{si} \): capacity of supplier \( s \) for supplying component \( i \)
- \( \text{CD}_{pkr} \): cost to distribute product \( p \) from DC \( k \) to retailer \( r \)
- \( \text{CDD}_{rv} \): distance between the SCOC \( c \) and RSP \( v \)
- \( \text{CFMR}_{pj} \): fixed cost for setting up plant \( j \) to manufacture product \( p \)
- \( \text{CLS}_{prec} \): product \( p \) collected via SCOC \( c \), as a percentage of demand at scenario \( e \)
- \( \text{CLR}_{pre} \): product \( p \) collected by retailer \( r \) as a percentage of demand at scenario \( e \)
- \( \text{CMR}_{pj} \): average production cost for product \( p \) in plant \( j \)
- \( \text{CT}_{pjk} \): cost to transport product \( p \) from plant \( j \) to DC \( k \)
- \( \text{CP}_{pc} \): cost to collect product \( p \) via SCOC \( c \)
- \( \text{CRC}_{pr} \): cost for retailer \( r \) to collect product \( p \)
- \( \text{CRV}_{iv} \): cost for RSP \( v \) to recover component \( i \)
- \( \text{CT}_{pjk} \): cost to transport product \( p \) from plant \( j \) to DC \( k \)
- \( \text{CW}_{pk} \): capacity of DC warehouse \( k \) to accommodate product \( p \)
- \( D_{ptr} \): demand of product \( p \) quality type \( t \) from retailer \( r \)
- \( DD_{jk} \): distribution distance between DC \( k \) and retailer \( r \)
- \( DSL \): set distance limit
- \( DST_{mer} \): distance between retailer \( r \) and \( r' \) of market \( m \)
- \( EI_{is} \): energy in MJ for supplier \( s \) to produce input \( i \)
- \( DSTT_{mer} \): distance between retailer \( r \) and SCOC \( c \) in market \( m \)
- \( EP_{pj} \): energy in MJ to produce product \( p \) in plant \( j \)
- \( ER_{iv} \): energy in MJ for recovery of input \( i \) by RSP \( v \)
- \( ET \): energy in MJ for per mile transportation or distribution of product by a truck
- \( FCC_{ci} \): fixed cost to install SCOC \( c \)
- \( FCR_{rj} \): fixed cost of retailer \( r \) for returns collection
- \( FRV_{pv} \): fixed cost to set up recovery process by RSP \( v \) for product \( p \)
- \( FW_{pk} \): fixed cost to open DC \( k \) for product \( p \)
- \( HEP_{pj} \): harmful emission in kg of CO2 equivalent to produce product \( p \) in plant \( j \)
- \( HEI_{is} \): harmful emission in kg of CO2 equivalent to produce input \( i \) by supplier \( s \)
- \( HET \): harmful emission in kg of CO2 equivalent per mile transportation or distribution of product by a truck
- \( IC_{is} \): Cost of procuring component \( i \) through supplier \( s \)
- \( M \): big positive number
- \( OC_{is} \): fixed cost for ordering component \( i \) to supplier \( s \)
- \( P_{se} \): probability of scenario \( e \) for collection of returns
- \( OC_{is} \): fixed cost for ordering component \( i \) to supplier \( s \)
- \( q_{c} \): 1 if plant \( j \) is quality capable, 0 otherwise;
- \( q_{a} \): 0/1 parameter, 1 if the supplier is quality affiliated, 0 otherwise
- \( RCP_{pv} \): recovery capacity of RSP \( v \) to recover components from returnable \( p \)
- \( P_{p} \): use of component \( i \) by product \( p \)
- \( T_{jk} \): transportation distance between plant \( j \) and DC \( k \)
- \( VP_{por} \): market price for product \( p \) of quality type \( t \) as agreed to be paid by retailer \( r \)

### 3.3 Mathematical Model for CLSC Planning

**Objective Function:** maximize Profit \( Z = REV - TC \) \((1)\)

The objective function in equation (1) maximizes profit, which is computed by subtracting the total SC cost (TC), as defined in (3) from the total revenue (REV), as defined in equation (2).

\[
REV = \sum_{p \in P} \sum_{i \in I} \sum_{r \in R} \sum_{r' \in R} \sum_{k \in K} VP_{pr} \sum_{k \in K} y_{pk} \quad (2)
\]

REV in equation (2) is earned by supplying new \((t=1)\), remanufactured \((t=2)\) and second-hand \((t=3)\) products to the retailer at the market price.

\[
TC = PRC + CC + RCPV + TDI + PENALTY \quad (3)
\]

Equation (3) defines total SC cost \((TC)\) in terms of its components; \( PRC \) is the product realization cost, \( CC \) is the collection cost for returns, \( RCPV \) is the recovery and procurement cost, \( TDI \) is the transportation and distribution cost, and \( PENALTY \) is the penalty cost for spent energy and harmful emissions.

The product realization cost, \( PRC \), as defined in (3.a), includes the manufacturing cost for three quality type products in the production plants and the fixed cost of setting the plants up for production. Equation (3.b) computes the collection cost for returns \((CC)\). \( CC \) considers the collection cost by SCOCs and the fixed cost of installing collection centers, the collection cost by retailers, and the cost of making collection arrangements through retailers. Equation (3.c) computes the procurement and recovery cost \((RCPV)\), which considers procurement and the fixed ordering cost for new components to suppliers, the recovery cost of components from returns to be paid to RSPs, and the fixed cost of allocating returns to RSPs. Equation (3.d) computes \((TDI)\) cost of transporting products from the plants to the DCs and distributing them from the DCs to the retailers, and the fixed cost of opening DC Warehouses. Equation (3.e) computes the \( PENALTY \) cost for spent energy and the generation of harmful emissions by the SC plants for the production of products, component processing by suppliers and recovery services by RSPs in addition to such items
during transportation and distribution (all of these items are accounted for by $TSE$ and $THE$). The cost of spent energy is computed by considering the cost per kWh of energy in the US industry and the total spent energy $TSE$ in kWh. To compute the penalty cost of harmful emissions, $THE$ in kg of equivalent CO$_2$ is multiplied by an equivalent $\$$ value based on the carbon tax imposed in Australia to restrict CO$_2$ emissions.

\[ PRC = \sum_{p \in P} \sum_{j \in J} CMR_{pj} \sum_{t \in T} \sum_{k \in K} x_{pjk} + \sum_{p \in P} \sum_{j \in J} CFMR_{pj} u_{pj} \]  
(3.a)

\[ CC = \sum_{p \in P} \sum_{c \in C} CP_{p} rC_{p} + \sum_{c \in C} a_{c} FCC_{c} + \sum_{p \in P} \sum_{r \in R} CRC_{p} rR_{p} + \sum_{r \in R} or_{r} FCr_{r} \]  
(3.b)

\[ RCPV = \sum_{i \in I} \sum_{s \in S} (IC_{i} z_{i} + OC_{i} z_{a_{i}}) + \sum_{i \in I} \sum_{v \in V} CRV_{i} rz_{i,v} + \sum_{p \in P} \sum_{v \in V} FRV_{p} ar_{p} \]  
(3.c)

\[ TDI = \sum_{p \in P} \sum_{j \in J} \sum_{k \in K} CT_{p} rC_{p} \sum_{s \in S} x_{pjk} + \sum_{p \in P} \sum_{k \in K} \sum_{r \in R} CD_{p} \sum_{s \in S} y_{pkr} + \sum_{p \in P} \sum_{k \in K} \sum_{r \in R} FW_{p} w_{p} \]  
(3.d)

\[ PENALTY = TSE \times Cost \text{ factor} + THE \times Factor \text{ for Carbon tax} \]  
(3.e)

Equation (4) defines the total of SC’s spent energy $TSE$ in terms of its components. $SEPM$, as defined in equation (4.a) computes the energy spent by the plants in manufacturing three quality type products. The second component of $TSE$, $SER$, as defined in (4.b) computes the energy spent in manufacturing new components by the suppliers and the recovery of inputs from returns by the RSPs. $SETD$, as defined in (4.c), is the last component of $TSE$ that computes the energy spent in transporting products from the plants to the DCs and distributing them from the DCs to the retailers, considering Plant–DC and DC–retailer distances, standard spent energy per unit distance, and number of standard truckload trips.

\[ TSE = SEPM + SER + SETD \]  
(4)

\[ SEPM = \sum_{p \in P} \sum_{j \in J} \sum_{s \in S} EP_{p} \sum_{t \in T} \sum_{k \in K} x_{pjk} \]  
(4.a)

\[ SER = \sum_{i \in I} \sum_{s \in S} EI_{i} z_{i} + \sum_{i \in I} \sum_{v \in V} ER_{i} rz_{i,v} \]  
(4.b)

\[ SETD = \sum_{j \in J} \sum_{k \in K} TD_{j} ET \sum_{p \in P} \sum_{t \in T} x_{pjk} / TL_{p} + \sum_{k \in K} \sum_{r \in R} DD_{j} ET \sum_{p \in P} \sum_{r \in R} y_{pkr} / TL_{p} + \]  
(4.c)

\[ ET = \frac{rc_{p} \sum_{i \in I} \sum_{s \in S} CD_{D_{i}}}{TL_{p}} \]  
(3.d)

\[ THE = EMR + EVR + ETD \]  
(5)

Equation (5) defines the total harmful emissions, $THE$, in terms of its components. The first component, $EMR$ as defined in (5.a) computes the harmful emissions generated in manufacturing products. The next component, $EVR$ as defined in (5.b) computes the harmful emissions generated in new component manufacturing and the recovery of inputs from returns. $ETD$, as defined in equation (5.c) computes the harmful emissions generated by the transportation of new and remanufactured products from the plants to the DCs and by the distribution of products from the DCs to the retailers, considering Plant–DC and DC–retailer distance combinations, standard harmful emissions per unit distance, and number of standard truckload trips.
\[ EMR = \sum_{p \in P} \sum_{J \in J} HEP_{pj} \sum_{r \in r} \sum_{k \in K} x_{pqk} \]  
\[ EVR = \sum_{j \in J} \sum_{k \in K} HEI_j z_{aj} + \sum_{j \in J} \sum_{v \in V} HER_j r_{vj} \]  
\[ ETD = \sum_{j \in J} \sum_{k \in K} TD_j HET \sum_{r \in r} \sum_{k \in K} x_{pqk} / TL_p + HET \sum_{k \in K} \sum_{r \in r} DD_k \sum_{r \in r} \sum_{s \in S} y_{psr} / TL_p + \]  
\[ HET(\sum_{p \in P} \sum_{v \in V} rc_{pv} \sum_{v \in V} CDD_v) / TL_p \]

Subject to:

\[ D_{pr} = \sum_{k \in K} y_{pkr} \quad \forall p, t, r \]  
\[ y_{pkr} \leq ak_{ij} M \quad \forall p, t, k, r \]  
\[ \sum_{r \in r} y_{pkr} = \sum_{j \in J} x_{pqk} \quad \forall p, t, k \]  
\[ \sum_{k \in K} \sum_{j \in J} x_{pqk} \leq u_p CAP_j \quad \forall p, j \]  
\[ \sum_{r \in r} x_{pqk} \leq w_{jk} CW_{pk} \quad \forall p, k \]  
\[ (DST_{mrj} - DSL) \leq po_{mrj} M \quad \forall m, c, r \neq r_i \]  
\[ -(DST_{mrj} - DSL) \leq (1 - po_{mrj}) M \quad \forall m, c, r \neq r_i \]  
\[ a_c = po_{mrj} \forall m, c, r, r_i \]  
\[ rc_{pv} = a_c (1 / (\sum |c| + |r|)) \sum_{r \in r} \sum_{k \in K} D_{pr} \sum_{p \in P} PS_{ps} CLS_{pc} \quad \forall p, c \]  
\[ r_{pr} = \sum_{r \in r} D_{pr} \sum_{v \in V} PS_{ps} CLR_{pv} \quad \forall p, r \]  
\[ r_{pr} \leq or M \quad \forall p, r \]  
\[ \sum_{v \in V} r_{pr} + \sum_{r \in r} r_{pr} = \sum_{v \in V} r_{pv} \quad \forall p \]  
\[ r_{pv} \leq ar_{pv} RCP_{pv} \quad \forall p, v \]  
\[ \sum_{p \in P} r_{pv} \rho_{pv} (1 - WS) = rz_{iv} \quad \forall i, v \]  
\[ \sum_{i \in I} \sum_{s \in S} x_{pqk} \rho_{ps} + \sum_{s \in S} \sum_{r \in r} y_{pkr} \rho_{ps} + \sum_{s \in S} \sum_{s \in S} \sum_{r \in r} y_{psr} \rho_{ps} + \sum_{s \in S} \sum_{i \in I} \sum_{s \in S} \sum_{r \in r} y_{psr} \rho_{ps} \quad \forall i \]  
\[ \sum_{p \in P} \sum_{j \in J} \sum_{k \in K} x_{pqk} \rho_{ps} + \sum_{s \in S} \sum_{i \in I} \sum_{s \in S} \sum_{r \in r} y_{psr} \rho_{ps} = \sum_{s \in S} \sum_{i \in I} \sum_{s \in S} \sum_{r \in r} y_{psr} \rho_{ps} \quad \forall i \]  
\[ z_{ui} \leq zs_{pi} CAS_{si} \quad \forall i \in I, s \]  
\[ z_{si} \leq qa \quad \forall i, s \]  
\[ u_{pj} \geq qc_{j} \quad \forall p, j \]  
\[ \sum_{j \in J} u_{pj} \geq 2 \quad \forall p \]  
\[ \sum_{s \in S} z_{si} \geq 2 \quad \forall i \]  
\[ ak_{ij} \in [0, 1], \forall k, r; u_{pj} \in [0, 1], \forall p, j; po_{mrj} \in [0, 1], \forall m, c, r, r_i; w_{jk} \in [0, 1], \forall p, k; \]  
\[ a_c \in [0, 1], \forall c; \quad or_{pv} \in [0, 1], \forall r; ar_{pv} \in [0, 1], \forall p, v; zs_{pi} \in [0, 1], \forall i, s; qc_{j} \in [0, 1], \forall j; \]  
\[ D_{pr}, x_{pqk}, y_{pkr}, z_{ui}, rz_{iv}, rz_{iv}, rc_{pv}, r_{pr} \]  
\[ \text{integers} \]  

Equation (6) balances the product demanded by the retailers with the product distributed to them from the DCs. Constraint (7) allocates the DCs to supply products to retailers. Constraint (8) balances the supply of products from
plants to DCs with the distribution of different quality level products from the DCs to retailers. Constraint (9) limits the production of products in the SC plants based on their capacity. Constraint (10) limits the transfer of products from the plants to the DCs based on their capacity. Constraints (11), (12) and (13) work in a combined way to decide the opening of suitable SCOC based on the set distance limit between two retailers. The equations (11) and (12) are formulated by including an auxiliary variable $p_{DC,ret}$ to create an if-then situation following sub-chapter 9.2 Formulating Integer Programming Problems by Winston (2004). Constraint (14) estimates the amount of the returns collected by the SCOCs using a scenario-based analysis. Similarly, constraint (15) estimates the returns collected by the retailers using a scenario-based analysis. Constraint (16) assigns a retailer to collect the product returns. Equation (17) accumulates the total amount of the returns collected by the SCOCs and retailers to assign them to RSPs. Constraint (18) limits the allocation of returns to RSPs based on their capacity for recovery. Equation (19) estimates the usable amount of recovered inputs based on input usage by standard products and average wastage. Equation (20) computes the number of new components needed to compliment the shortages in recovered components for remanufactured/secondhand products. Constraint (21) balances the total new components by considering the components for manufacturing to be new ($i = 1$) and the components needed to supplement shortages in the recovered components obtained in (20). Constraint (22) limits the new components to be assigned to a supplier based on its capacity. The SC follows supplier quality affiliation procedure by using critical to quality and critical to business evaluation metric for identifying quality affiliated ensured quality supplier by 0/1 parameter $q_{au}$, to verify each supplier in constraint (23) following Das (2011). By applying quality capability determination procedure using different quality and capability evaluation metrics, capable plants are also similarly identified by 0/1 parameter $q_{cp}$ for each plant and then verified in constraint (24) for product plant combinations following Das (2011). According to constraint (25), each product is assigned to at least two plants to ensure capacity flexibility, and constraint (26) ensures that inputs are assigned to at least two suppliers to create supply flexibility. Constraints (25) to (26) are included to make the CLSCs resilient by including supply and capacity flexibility so that they will, in turn, contribute to economic sustainability. Constraints (26) and (27) impose integrality.

4. NUMERICAL EXAMPLE

For illustrating the applicability and effectiveness of the model we solved three examples of SC Case problems. Various model parameters, objective function values and typical model outcomes for the solution of the three SCs are presented in Table 2.

The model has been solved for the example problems using commercial Solver Lingo 14 using a Dell Latitude 5590 Personal Computer with Windows 10 operating System, having Intel® Core™ i7-8650U CPU@1.90GHz 2.11GHz with installed memory 16 GB.

For the SC Case 1 Problem with 7 products, 22 components, manufactured in 6 plants and marketed through 12 retailers the model involved 8,178 total variables, 4,663 integer variables, and 7,637 constraints, and took approximately 1-minute time for obtaining the global optimum solution. For the SC Case 2 Problem with 9 products, 24 components, manufactured in 6 plants and marketed through 12 retailers the model involved 14,154 total variables, 8,460 integer variables and 13,814 constraints, and took 1 hour 32 minutes for obtaining global optimum solution. For the SC Case 3 Problem with 6 products, 16 components, manufactured in 4 plants and marketed through 10 retailers the model involved 5,703 total variables, 2,997 integer variables and 5,282 constraints, and took 7 minutes for obtaining global optimum solution.

The SC cases 1, 2, and 3 manufacture 7, 9, and 6 products, respectively, by using 22, 24, and 16 components as described in Table 2. Further details for typical component use by the products of SC cases are shown in Table 3 to follow. After the input information on products and components, Table 2 presents the model solutions. Objective function values profit for SC Case Problems 1, 2 and 3 are $36.9$, $50.79$; and $26.35$ million, respectively; and the relevant revenue figures for resulting these profits are $116.15$, $174.62$ and $87.99$ million, respectively. Table 2 next presents basic information for model results. Average market prices for the products of SC cases 1, 2, and 3 are $143.5$, $143.10$ and $142.6$, respectively and the overall demand of products for the SC cases (considering new, remanufactured and secondhand) are $510,338$, $862,521$, and $381,382$, respectively as shown in Table 2. For further illustration on product demand Table 4 to follow presents model solutions for the production of each new, remanufactured, and second-hand products of these three SC cases 1, 2, and 3, respectively, for fulfilling market demand. Since average market price of the products of SC cases 1, 2, and 3 are almost identical, based on the comparison of overall product demand described above and the detailed model decisions to produce new, remanufactured, and second-hand product presented in Table 4 for the SC cases the profit, revenue, and total SC cost figures included in Table 2 may be considered logical and reasonable. According to Table 2 the SC Cases 1, 2, and 3 market their products in 5, 6; and 4 markets, respectively, using 12, 14, and 10 retailers in their respective markets.

Each of these retailers is independent. Although, each SC case uses the same retailer identifications number (such as 1 to 12 for SC case 1) distances between the retailers are different in different markets (See Appendix Table 1.1 and Table 1.2 for the distances between the Retailers of Markets 1 and 2 for SC case problem 1. SC Cases 2 and 3 have similar independent retailers with unique random locations for each market. As such distances between the retailers are different from one market to next. To illustrate, based on Appendix Table1.1 for Market 1 of SC case 1, distance between Retailers 2 and 3 is 115 minutes (equivalent to traveling distance), whereas for Market 2 distance between Retailers 2 and 3 is 81 minutes. Such differences in distances are applicable for all retailer combinations when retailers from market to market are different and independent.
Next, Table 2 presents model decisions on the allocation of total 6, 7, and 4 plants for managing the production of required products of SC cases 1, 2 and 3, respectively. Based on Table 2 the model allocated 2 to 3 plants for each of the products of SC cases. By allocating more than one plant for a product the model ensured capacity flexibility, which in turn will provide the SC cases economic sustainability and resilience for facing plant failure risks. For example, the model allocated plants 3, 5, 6 of SC Case 1 for producing product 1 (Table 2). As may be observed in Table 2, the model allocated 2 to 3 plants for each product of SC cases 1, 2 and 3. Table 2 next presents the allocation of two DCs to distribute products to each retailer to ensure distribution flexibility and by that creating resiliency for the failure of a DC due to some disruptions, and thus contribute to the improvement of economic sustainability. For example, retailer 1 of SC case 1 is allocated DCs 1 and 2; whereas for SC case 2, the model allocated DCs 2 and 3 for retailer 1. Table 2 next presents the assignment of supply orders to 2 or more suppliers for each of the components of SC cases 1, 2, and 3 for ensuring supply flexibility and thus to improve economic sustainability and supply resiliency.
the model assigned orders for component 1 of SC case 1 to suppliers 4 and 10 (Table 2).

The CLSC model next estimates the collection of customer returns through the retailers and SCOCs located between retailers when the distances between the retailers in a market exceed SC’s set limit of 120 minutes (traveling time equivalent to distances). Table 5 to follow presents model outcomes for the collection of returns by retailers and SCOCs. Table 2 presents model decisions on the opening of SCOCs in markets between two retailers for SC cases 1,2, and 3 when the distance between them exceeded the set limit of distances equivalent to 120 minutes of traveling times. Since retailers from market to market of a SC case are different, SCOCs are opened accordingly. For example, for Market 1 of SC case 1 the model could open 2 SCOCs and for Market 2 the model opened 3 SCOCs. Table 2 presents retail outlets between which each of the SCOCs opened. To illustrate, SCOC 1 is opened between retail outlets 2 and 12 of Market 1, for example (Table 2). Appendix Table 1.1 and 1.2 present details of positions of the SCOCs (highlighted in Yellow color) in Market 1 and Market 2 of SC case 1. The position of SCOC are shown in Appendix Tables 1.1 and 1.2 by the distance 120 minutes between retailers, which is equal to set limit DSL=120 minutes.

The collected returns by the retailers and SCOCs are assigned to RSPs for dismantling and component recovery. The model assigned recovery orders for the returns of SC cases 1,2 and 3 to 6,7 and 6 RSPs (Table 2).

4.1 Further Illustrations and Explanations of Table 2 Results

Table 3 below presents typical component use by the three products of SC cases 1,2, and 3. For example, product 1 of SC Case 1 use 11 components comprising of {2, 4, 5, 8, 9, 10, 12, 14, 16, 17, 18}; product 1 of SC Case 2 use 12 components {2, 3, 6, 8, 10, 11, 12, 14,17,20,21,22} and product 1 of SC Case 3 use 8 components {2,4,5,7,8,10,13,14}.

| Component | SC Case 1 | SC Case 2 | SC Case 3 |
|-----------|-----------|-----------|-----------|
| Product 1 | 2,4,5,8,9,10,11 | 2,3,6,8,10,11 | 2,4,5,7,8,10,13 |
| Product 2 | 12,14,17,20,21 | 1,2 | 14 |

Table 4 presents model solutions for the production of each new, remanufactured, and secondhand product by SC cases 1,2, and 3, respectively, for fulfilling market demand. For example, the model decided to produce new, remanufactured, and second-hand quality product 1 for SC case 1 is 71,491, 50,203; and 20,997, respectively for fulfilling market demand. Similar model decisions to produce other products of SC Case 1 as well as for the SC cases 2 and 3 may be observed in Table 4. Considering objective function values presented in Table 2, these production figures for the SC Cases may be considered logical and reasonable.

For further illustrations, typical demand for product 1 from retailers are shown in Table 4a. Based on Table 4a, demand for new product 1 from retailer 1 is 5,551; Table 4a also verifies the total demand of new product 1 (71,491) when we sum up the demand of product 1 from 12 retailers of SC Case 1.

Table 5 presents model solutions for estimated customer returns in the equivalent number of products collected by retailers for SC cases. For example, Product 1 returns collected by Retailers and SCOCs of SC case 1 are 42,510 and 14,174, respectively (Table 5). Similar collection figures for product types and SC cases may be observed in Table 5.
For motivating customers returns the SC Case problems considered an incentive scheme. The incentive scheme is included on the product label for keeping the customer informed from the time of buying the product. According to this scheme, four scenarios of customer returns are assumed considering the incentives to be paid to the customer for a particular condition of returned product with the probability of each scenario to be 25%. According to this scheme, the customer is offered 75% to 80% of the product value (cost of product) if 100% of the components of the product are in good recoverable condition, 60% of the value if 70% of the components are in good condition, 40% of the value if 50% of the components are recoverable, and 25% of the value if 30 to 35% of the components may be estimated to be in good condition. Typical scenarios and estimation of collectibles as used in the model are described here for illustrations:

Scenario 1(SC1): 75% to 80% of product value as the incentive to customer for customer returns with 100% components are in good useable condition, assumed return 70 % to 75% of demand with probability 0.25, so typical maximum collectible proportion 0.1875 of demand.

SC 2: 60 % to 65% of product value as the incentive to customer for customer returns with 70% of the components are in good condition, assumed % product return by such incentive ranges 55% to 60% with probability 0.25, so typical maximum collectible proportion (0.25*60) = 0.15 of demand.

SC 3: 35% to 40 % of the value as the incentive when the customer returns assumed to have 50% components in good condition, assumed % product return by such incentive: 35% to 40% of product demand with probability 0.25, typical maximum collectible proportion 0.1 of demand

SC 4: 25% to 30% of the product value as the incentive when 30% to 35% of the components from product returns are assumed to be in good condition; assumed % product returns by such incentive 20% to 25% with probability 0.25, typical maximum collectible proportion of returns =0.0625 of demand.

0.75,0.60, 0.40, and 0.25 are typical maximum returnable values to CLR_{pre} and CLS_{pre} used in equation (14) and (15) and then these were multiplied by the probability of scenario as may be seen in Equation (14 and 15). For example, for SC case 1, CLR_{pre} for four scenarios are 0.78,0.57, 0.38, and 0.24 (here is e-is the scenario). Probability of scenario=0.25). Such percentage of product return values are almost the same for the remaining two cases with 5% to 10% random variation. As such % of collection according to equation (15): for SC case 1, PRE=0.78*0.25 +0.57*0.25+ 0.38*0.25 = 0.3975; Since Demand for new product 1 from Retailer1=5,551, so estimated amount of product 1 collected by retailer 1 for SC case 1 is:0.3975*5551=2206, for example.

Table 4a Demand for new product 1 for SC Case 1 for illustration

| Demand of product 1 (Type 1, new) from Retailers |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      | 10     | 11     | 12     |
| 5,551  | 6,019  | 6,354  | 5,804  | 6,322  | 5,701  | 6,518  | 5,624  | 5,624  | 5,785  | 6,212  | 5,977  |

Table 5 Collected customer returns for the products of SC cases 1, 2, and 3

| Collected Returns | 1        | 2        | 3        | 4        | 5        | 6        | 7        | 8        | 9        |
|------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| SC Case 1        |          |          |          |          |          |          |          |          |          |
| By retailers     | 42,510   | 51,471   | 44,534   | 41,648   | 35,067   | 30,023   | 29,541   | 25,023   | 22,541   |
| By SCOCs        | 14,174   | 17,184   | 14,850   | 13,815   | 11,738   | 10,823   | 10,011   | 9,723    | 9,611    |
| SC Case 2        |          |          |          |          |          |          |          |          |          |
| By retailers     | 63,605   | 37,195   | 52,317   | 48,939   | 49,505   | 49,411   | 35,023   | 30,023   | 22,541   |
| By SCOCs        | 25,234   | 14,448   | 20,541   | 19,483   | 19,912   | 20,011   | 14,477   | 16,667   | 22,355   |
| SC Case 3        |          |          |          |          |          |          |          |          |          |
| By retailers     | 32,149   | 33,128   | 34,364   | 31,313   | 31,771   | 30,972   |          |          |          |
| By SCOCs        | 12,872   | 13,344   | 13,777   | 12,908   | 13,292   | 12,809   |          |          |          |

Table 6 presents the quantity of recovered components by the RSPs of SC cases from the collected returns in Table 5. For example, according to Table 6 RSPs of SC Case 1 recovered 104,137 components 1 from collected returns by retailers and SCOCs in Table 5. Table 6 presents the quantity of the entire 22 components for SC case 1 and the relevant components of SC cases 2 and 3.

The SC procures new components from the suppliers, recovered components from RSPs, and then allocates production to plants considering costs, sustainability metrics in terms of spent energy, and harmful emissions to realize the items.
Based on data for overall spent energy and generation of harmful emission the penalty cost is computed by considering the US energy rate in the industry, $0.2 per kWh. After converting total spent energy in MJ to kWh (3.6 MJ = 1 kWh), the penalty factor for total energy spent was (1/3.6) *0.2≈0.056. For harmful emissions, the penalty factor was (1/1000) *51 ≈ 0.051, considering total emissions in tons of CO₂ and per ton penalty $51 as used by Australia (Fahmina et al., 2013). Based on Table 7, it is evident that by improving environmental sustainability through the reduction of energy consumption and the generation of harmful emissions the SC can improve economic sustainability.

The model considered costs, spent energy, and harmful emission for assigning recovery services to RSP, production to plants, new inputs to suppliers, and transportation routes for product transfer to DCs, and distribution to retailers to optimize profit. Using these, the model improves sustainability performances for SC Cases 1, 2, and 3 including data for all other processes in addition to manufacturing remanufacturing can be seen in Table 7. It may be mentioned here that for estimating total fuel energy spent and generated harmful emissions for Transportation of product for Plant-DC combinations and distribution of product for DC-retailer combinations we used the fuel energy spent (24.80 MJ/mile, US DOT, 2012) and the harmful emissions generated (0.46 kg/mile in equivalent CO₂ (CATF, 2009; NGHAF, 2013).

### Table 6 Quantity of recovered components (CN) from returns in Table 5 by the RSPs of SC cases

| CN | Quantity | CN | Quantity | CN | Quantity | CN | Quantity |
|----|----------|----|----------|----|----------|----|----------|
| 1  | 104,137  | 13 | 214,714  | 1  | 178,166  | 13 | 283,305  |
| 2  | 102,818  | 14 | 209,586  | 2  | 291,393  | 14 | 416,279  |
| 3  | 201,785  | 15 | 161,444  | 3  | 215,295  | 15 | 72,224   |
| 4  | 98,561   | 16 | 202,774  | 4  | 130,137  | 16 | 192,931  |
| 5  | 211,346  | 17 | 315,853  | 5  | 306,692  | 17 | 358,300  |
| 6  | 216,780  | 18 | 150,161  | 6  | 423,645  | 18 | 394,063  |
| 7  | 273,504  | 19 | 101,120  | 7  | 110,892  | 19 | 158,507  |
| 8  | 263,145  | 20 | 216,845  | 8  | 199,998  | 20 | 427,642  |
| 9  | 270,633  | 21 | 217,079  | 9  | 232,492  | 21 | 319,090  |
| 10 | 151,357  | 22 | 216,640  | 10 | 212,093  | 22 | 347,483  |
| 11 | 150,438  | 23 | 192,410  | 11 | 106,854  | 23 | 122,568  |
| 12 | 304,374  | 24 | 319,756  | 12 | 279,031  | 24 | 85,027   |

### Table 7 Summary of energy spent, and harmful emissions generated by the SC cases 1, 2, and 3

| SC Environmental sustainability factors | Manufacturing and remanufacturing products | New component manufacturing | Component recovery | Transportation and distribution | Total | Penalty in M($) |
|----------------------------------------|--------------------------------------------|----------------------------|--------------------|--------------------------------|-------|-----------------|
| SC Case 1                              |                                            |                            |                    |                                |       |                 |
| Spent Energy (MJ), Million              | 14.44                                      | 67.61                      | 35.75              | 22.64                          | 140.44| 7.86            |
| Harmful Emission, Million Kgs of CO₂   | 5.19                                       | 36.69                      | 22.18              | 0.438                          | 64.50 | 3.29            |
| SC Case 2                              |                                            |                            |                    |                                |       |                 |
| Spent Energy (MJ), Million              | 15.33                                      | 58.72                      | 53.43              | 29.46                          | 156.94| 8.79            |
| Harmful Emission, Kgs of CO₂            | 8.6                                        | 37.27                      | 30.72              | 0.57                           | 77.16 | 3.94            |
| SC Case 3                              |                                            |                            |                    |                                |       |                 |
| Spent Energy (MJ), Million              | 6.9                                        | 36.77                      | 21.35              | 13.26                          | 78.28 | 4.38            |
| Harmful Emission, Kgs of CO₂            | 2.98                                       | 16.03                      | 23.23              | 0.26                           | 42.5  | 2.16            |
applicability and validation of transportation and distribution quantity of products based on the Appendix Tables and illustration there. It may be mentioned here that the model decided transportation and distribution routes to obtain optimal costs and sustainability metrics for spent energy and harmful emissions.

Based on the above analysis of the model results, considering changes of parameters, problem entities for the illustrated three SC cases the overall outcomes of the CLSC planning model could effectively address environmental sustainability and economic sustainability factors to maximize overall SC profit. The outcomes for the three SC cases based on the inputs and production figures may be considered logical.

5. CONCLUSION

This research introduces a detailed approach to integrating environmental and economic sustainability issues in a CLSC planning model. It plans a forward loop of an SC by considering capacity and supply flexibility to render the SC economically sustainable by making it reasonably resilient. To improve sustainability performances, it plans the collection of customer returns through retailers and SCOCs, along with the recovery of usable components through a pool of RSPs in the reverse loop. The approach involves planning the quality enhancement of recovered components for remanufactured products to improve SCs’ economic sustainability, quality, and green image. The model and overall approach, as much as possible, use the recovered components by including second-hand products in the product portfolio to expand SCs’ environmental and economic sustainability performances. The model selects quality capable plants to ensure product quality and optimizes LCA metrics; namely, spent energy and harmful emissions, by selecting appropriate production plants and transportation routes. Overall, the model facilitates the improvement of environmental and economic sustainability by reducing various system waste and including product choices and flexibility measures. Future research may explore the model’s application in a real-world business case.

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APPENDIX 1

Appendix Table 1.1: demonstrating distances between the retailers, and Model outcomes for opening typical SCOCs based on distances becoming ≥ set distance 120 minutes for Market 1 of SC case 1).

| Market 1 | Retailer for SC case 1 |
|----------|------------------------|
|          | Retailer 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1        | 0          | 95 | 93 | 65 | 76 | 83 | 103 | 96 | 92 | 66 | 78 | 88 |
| 2        | 65         | 94 | 92 | 65 | 76 | 83 | 110 | 83 | 77 | 84 | 90 | 120 |
| 3        | 76         | 91 | 89 | 105 | 0 | 77 | 74 | 79 | 92 | 91 | 78 | 75 |
| 4        | 83         | 89 | 65 | 78 | 77 | 0 | 98 | 62 | 73 | 99 | 78 | 92 |
| 5        | 103        | 91 | 79 | 68 | 74 | 98 | 0 | 78 | 107 | 75 | 68 | 90 |
| 6        | 96         | 63 | 110 | 81 | 79 | 62 | 78 | 0 | 71 | 81 | 97 | 84 |
| 7        | 92         | 86 | 83 | 88 | 92 | 73 | 107 | 71 | 0 | 89 | 104 | 92 |
| 8        | 66         | 67 | 77 | 68 | 91 | 99 | 75 | 81 | 89 | 0 | 120 | 96 |
| 9        | 78         | 88 | 84 | 85 | 78 | 78 | 68 | 97 | 104 | 120 | 0 | 69 |
| 10       | 88         | 120 | 90 | 72 | 75 | 92 | 90 | 84 | 92 | 96 | 69 | 0 |

Appendix Table 1.1 presents distances (in terms of travelling time in minutes) between retailers of market 1 for SC Case 1. As mentioned in Table 2 the model decides opening SCOC when distances between retailers ≥120 minutes. For an example, the model opened SCOCs between (Retailer 2 and 12, and (10,11) finding distances between the retailers 120 minutes, which is the set limit by SC case 1.

Appendix Table 1.2: demonstrating distances between the retailers, and Model outcomes for opening typical SCOCs based on distances becoming ≥ set distance 120 minutes for Market 2 of SC case 1).

| Market 2 | Retailer for SC case 1 |
|----------|------------------------|
|          | Retailer 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1        | 0          | 56 | 62 | 93 | 104 | 75 | 64 | 92 | 100 | 88 | 120 | 71 |
| 2        | 56         | 0 | 81 | 110 | 86 | 64 | 62 | 121 | 87 | 107 | 109 | 68 |
| 3        | 62         | 81 | 0 | 117 | 86 | 72 | 90 | 71 | 117 | 112 | 61 | 83 |
| 4        | 93         | 110 | 117 | 0 | 79 | 59 | 71 | 104 | 65 | 88 | 72 | 112 |
| 5        | 104        | 86 | 86 | 79 | 0 | 70 | 121 | 88 | 104 | 92 | 96 | 98 |
| 6        | 75         | 64 | 72 | 59 | 70 | 0 | 88 | 61 | 84 | 90 | 60 | 74 |
| 7        | 64         | 62 | 90 | 71 | 121 | 88 | 0 | 120 | 63 | 87 | 58 | 71 |
| 8        | 92         | 121 | 71 | 104 | 88 | 61 | 120 | 0 | 82 | 98 | 114 | 101 |
| 9        | 100        | 87 | 117 | 65 | 104 | 84 | 63 | 82 | 0 | 94 | 116 | 120 |
| 10       | 88         | 107 | 112 | 88 | 92 | 90 | 87 | 96 | 98 | 0 | 92 | 112 |
| 11       | 120        | 109 | 61 | 72 | 96 | 60 | 58 | 114 | 116 | 92 | 0 | 67 |
| 12       | 71         | 68 | 83 | 112 | 98 | 74 | 71 | 101 | 120 | 112 | 67 | 0 |

In the case of Market 2 of SC case 1, the model had the option to open three SCOCs (See Appendix Table 1.2 above); between retailers (1,11); (7,8), (9,12) since distances in each case is 120, which is ≥ limit set by the SC case 1.
Appendix Table 2.1: Typical model decision for distributing total product (all types) from DCs to Retailer for product 1 and 5 of SC case 1

| SC case 1 | Product1 |
|-----------|----------|
| DCs       | 1 2 3 4 5 6 7 8 9 10 11 12 |
| 1         |         |         |         |         |         |         |         |         |         |         |         |
| 2         | 11,316  11,815 12,573 4,965 11,583 |         |         |         |         |         |         |         |         |         |         |
| 3         |         |         |         |         |         |         |         |         |         |         |         |
| 4         | 12,397  12,469 |         |         |         |         |         |         |         |         |         |         |
| 5         |         |         |         |         |         |         |         |         |         |         |         |

Appendix Table 2.2: Typical model decision for distributing product from DCs to Retailer for product 1 and 2 of SC case 2

| SC case 2 | Product1 |
|-----------|----------|
| DCs       | 1 2 3 4 to 7 8 9 10 11 12 13 14 |
| 1         | 13,485 | 14,226 | 16,197 |
| 2         | 2,418  | 15,285 |
| 3         |         | 326    |
| 4         | 3,677  | 16,195 | 16,428 |
| 5         | 9,992  | 10,201 | 5,643  | 9,712  |

Appendix Tables 2.1 and 2.2 demonstrates distribution of product from DCs to Retailer. For an example, based on Appendix Table 2.1 Retailers 1, 2, 7, 8 and 10 are distributed from DC 2 for an example. Based on Table 2 Data on 0/1 variable \( a_{kr} \) for allocation of DC \( k \) to supply retailer \( r \) DC 2 is allocated as one of the DCs to supply retailer 1, 2, 7, 8, and 10. As such the model correctly distributed product to retailers. Overall distributed quantity of product by the DC 2 to retailers are: \((11,316 + 11,815 + 12,573 + 4,965 + 11,583) = 52,252\). Appendix Table 3.1 shows the Supply or transportation of product from plant to DCs. Appendix Table 3.1 presents the products transported from the production plants to DC 2 is 52,252, which establishes balancing of distributed quantity of product from DC 2 to retailers in this typical case. (Appendix Table 3.1.) Similar verification on balancing of supply to DCs from the production plants and distribution from DCs to retailer may be done for all the products in the three SC cases.
Appendix Table 3.1: Transportation of all types (New remanufactured, second-hand) of product from Plant to DC

| Product | 1     | 2     | 3     | 4     | 5     | Grand total |
|---------|-------|-------|-------|-------|-------|-------------|
| 1       | 52,252| 7,036 | 37,100| 46,303|       | 142691      |
| 2       | 47,634| 55,342| 56,508|       | 10,658| 170142      |
| 3       | 14,837| 49,743| 37,583| 47,085|       | 149248      |
| 4       | 22,991| 45,459| 1,094 | 25,729| 44,271| 139544      |
| 5       | 34,000| 23,930| 14,272| 9,529 | 35,548| 117279      |
| 6       | 2,515 | 52,829| 3,247 | 50,852| 55,821| 165264      |
| 7       | 12,506| 45,355| 41,286| 19,645| 13,653| 132445      |

As discussed above Appendix Table 3.1 presents transported quantity of products from production plants to Distribution centers such that they can fulfill requirements of products by retailer to satisfy market demand. For example 14,837 product 3 have been transported from the production plants to DC 1, as may be observed in Appendix Table 3.1.

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