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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 inddition to improving plant reliability and thus processing capability. CLSCs with quality assurance-based supply and manufacturing management integrate resiliency 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	a)	√	√	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
Reimann *et al.*, (2019)	a)	√	X	c)	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* rr_{pr} defines collection of returnable by retailer in the model equation (3.b); *d*)SC operated collection center; *variable* rc_{pc} defines collection of returnable by SC operated outlets in model equation (3.b) ; ***e***) and collection by vendor by f) offering incentives ; paid by retailer and is 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_s *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_j 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 po_{mcrr1} in between retailers to improve product returns, thus improve environmental sustainability and customer service in turn economic sustainability. "X" means not addressed; "√" considered.

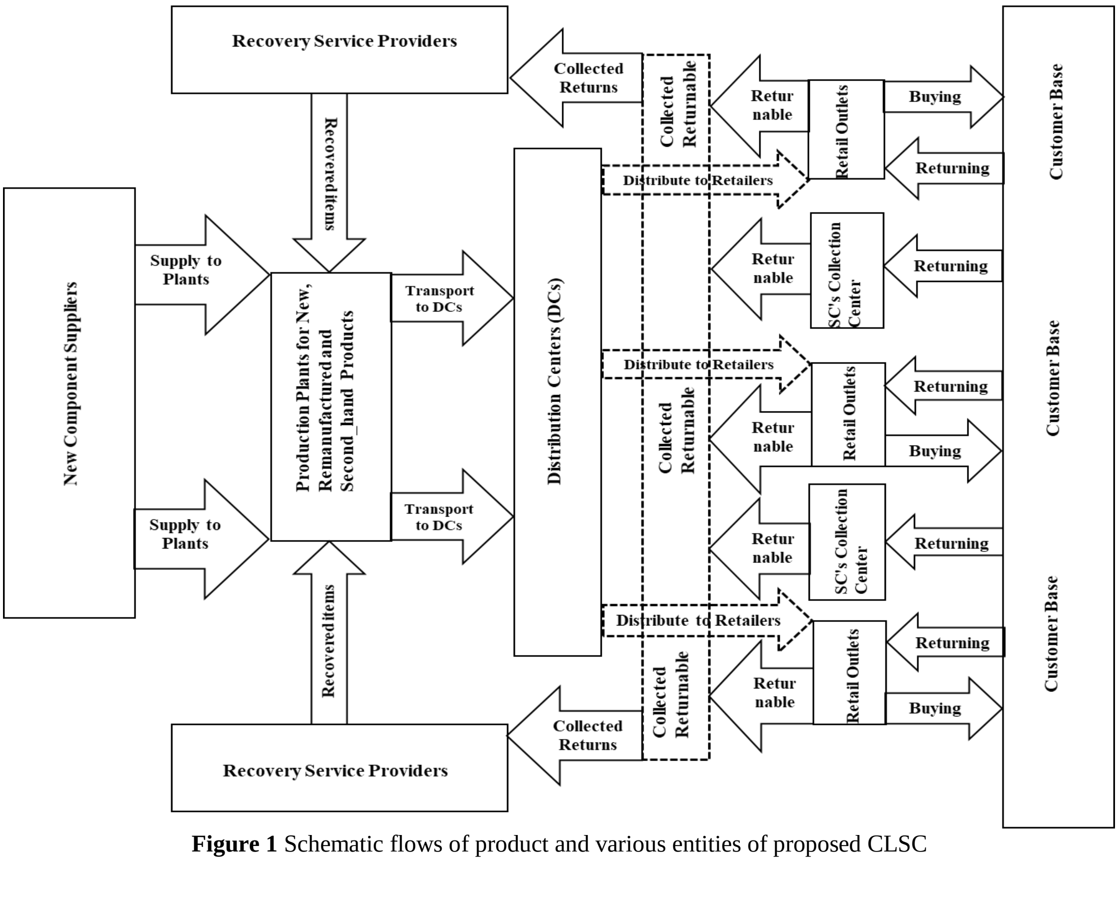

Figure 1 Schematic flows of product and various entities of proposed CLSC

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 researches 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, Ovchinnikov 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. Bhattacharya 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 Cetnikaya (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_{ptjk} 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_{ptkr} 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 po_{mcrr1} = 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); nz_{is} 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. $rz_{i'v}$ 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/recovered / second-hand / remanufactured) product $p \in P$
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_c	:	1 if collection center c is opened, 0 otherwise
ak_{kr}	:	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
nz_{is}	:	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
po_{mcrr1}	:	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
$rz_{i'v}$	:	input i' recovered by RSP v
u_{pj}	:	1 if production of product p is set for producing in plant j, 0 otherwise
w_{pk}	:	1 if DC k is open to accept product p, 0 otherwise
x_{ptjk}	:	product p of quality type t manufactured in plant j to transport to distribution center k
y_{ptkr}	:	product p of quality type t distributed from DC k to retailer r

y_{krr1} : an auxiliary 0/1 decision variable to facilitate opening a SC's own operated collection center between retailer *r* and *r1*
z_{is} : input *i* procured from supplier *s* (new inputs/components)

Parameters:

CAP_{pj} : capacity of producing product *p* in plant *j*
CAS_{is} : capacity of supplier *s* for supplying component *i*
CD_{pkr} : cost to distribute product *p* from DC *k* to retailer *r*
CDD_{cv} : distance between the SCOC *c* and RSP *v*
$CFMR_{pj}$: fixed cost for setting up plant *j* to manufacture product *p*
CLS_{pce} : product *p* collected via SCOC *c*, as a percentage of demand at scenario *e*
CLR_{pre} : product *p* collected by retailer *r* as a percentage of demand at scenario *e*
CMR_{pj} : average production cost for product *p* in plant *j*
CT_{pjk} : cost to transport product *p* from plant *j* to DC *k*
CP_{pc} : cost to collect product *p* via SCOC *c*
CRC_{pr} : cost for retailer *r* to collect product *p*
CRV_{iv} : cost for RSP *v* to recover component *i*
CT_{pjk} : cost to transport product *p* from plant *j* to DC *k*
CW_{pk} : capacity of DC warehouse *k* to accommodate product *p*
D_{ptr} : demand of product *p* quality type *t* from retailer *r*
DD_{kr} : distribution distance between DC *k* and retailer *r*
DSL : set distance limit
DST_{mrr1} : distance between retailer *r* and r_1 of market *m*
EI_{is} : energy in MJ for supplier *s* to produce input *i*
$DSTT_{mrc}$: 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_c : fixed cost to install SCOC *c*
FCR_r : 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 CO_2 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*
PS_e : probability of scenario *e* for collection of returns
OC_{is} : fixed cost for ordering component *i* to supplier *s*
qc_j : 1 if plant *j* is quality capable, 0 otherwise;
qa_s : 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*
ρ_{ip} : use of component *i* by product *p*
TD_{jk} : transportation distance between plant *j* and DC *k*
TL_p : standard truckload for product *p*
VP_{ptr} : 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).

$$REV = \sum_{p\in P} \sum_{t\in T} \sum_{r\in R} VP_{ptr} \sum_{k\in K} y_{ptkr} \tag{2}$$

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.

$$TC = PRC+CC+RCPV+TDI+PENALTY \tag{3}$$

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.

$$PRC = \sum_{p\in P}\sum_{j\in J} CMR_{pj}\sum_{t\in T}\sum_{k\in K} x_{ptjk} + \sum_{p\in P}\sum_{j\in J} CFMR_{pj}u_{pj} \tag{3.a}$$

$$CC = \sum_{p\in P}\sum_{c\in C} CP_{pc}rc_{pc} + \sum_{c\in C} a_c FCC_c + \sum_{p\in P}\sum_{r\in R} CRC_{pr}rr_{pr} + \sum_{r\in R} or_r FCr_r \tag{3.b}$$

$$RCPV = \sum_{i\in I}\sum_{s\in S}(IC_{is}z_{is} + OC_{is}za_{is}) + \sum_{i'\in I}\sum_{v\in V} CRV_{iv}rz_{i'v} + \sum_{p\in P}\sum_{v\in V} FRV_{pv'}ar_{pv} \tag{3.c}$$

$$TDI = \sum_{p\in P}\sum_{j\in J}\sum_{k\in K} CT_{pjk}\sum_{t\in T} x_{ptjk} + \sum_{p\in P}\sum_{k\in K}\sum_{r\in R} CD_{pkr}\sum_{t\in T} y_{ptkr} + \sum_{p\in P}\sum_{k\in K} FW_{pk}w_{pk} \tag{3.d}$$

$$PENALTY = TSE*Cost\ factor + THE*Factor\ for\ Carbon\ tax \tag{3.e}$$

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.

$$TSE = SEPM + SER + SETD \tag{4}$$

$$SEPM = \sum_{p\in P}\sum_{j\in J} EP_{pj}\sum_{t\in T}\sum_{k\in K} x_{ptjk} \tag{4.a}$$

$$SER = \sum_{i\in I}\sum_{s\in S} EI_{is}z_{is} + \sum_{i\in I}\sum_{v\in V} ER_{iv}rz_{iv} \tag{4.b}$$

$$SETD = \sum_{j\in J}\sum_{k\in K} TD_{jk}ET\sum_{p\in P}\sum_{t\in T} x_{ptjk}/TL_p + \sum_{k\in K}\sum_{r\in R} DD_{kr}ET\sum_{p\in P}\sum_{t\in T} y_{ptkr}/TL_p + ET\Big(\sum_{p\in P}\sum_{c\in C} rc_{pc}\sum_{v\in V} CDD_{cv}\Big)/TL_p \tag{4.c}$$

$$THE = EMR + EVR + ETD \tag{5}$$

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.

$$EMR = \sum_{p \in P} \sum_{j \in J} HEP_{pj} \cdot \sum_{t \in T} \sum_{k \in K} x_{ptjk} \tag{5.a}$$

$$EVR = \sum_{i \in I} \sum_{s \in S} HEI_{is} z_{is} + \sum_{i \in I} \sum_{v \in V} HER_{iv} rz_{iv} \tag{5.b}$$

$$ETD = \sum_{j \in J} \sum_{k \in K} TD_{jk} HET \sum_{p \in P} \sum_{t \in T} x_{ptjk} / TL_p + HET \sum_{k \in K} \sum_{r \in R} DD_{kr} \cdot \sum_{p \in P} \sum_{t \in T} y_{ptkr} / TL_p + HET(\sum_{p' \in P} \sum_{c \in C} rc_{pc} \sum_{v \in V} CDD_{cv}) / TL_p \tag{5.c}$$

Subject to:

$$D_{ptr} = \sum_{k \in K} y_{ptkr} \quad \forall p, t, r \tag{6}$$

$$y_{ptkr} \leq ak_{kr}.M \quad \forall p, t; k, r \tag{7}$$

$$\sum_{r \in R} y_{ptkr} = \sum_{j \in J} x_{ptjk} \quad \forall p, t; k \tag{8}$$

$$\sum_{k \in K} \sum_{t \in T} x_{ptjk} \leq u_{pj} CAP_{pj} \quad \forall p, j \tag{9}$$

$$\sum_{t \in T} \sum_{j \in J} x_{ptjk} \leq w_{pk} CW_{pk} \quad \forall p, k \tag{10}$$

$$(DST_{mrr1} - DSL) \leq po_{mrr1} M \quad \forall m, c, r \neq r_1 \tag{11}$$

$$-(DST_{mrr1} - DSL) \leq (1 - po_{mrr1}) M \quad \forall m, c, r \neq r_1 \tag{12}$$

$$a_c = po_{mcrr_1} \quad \forall m, c, r, r_1 \tag{13}$$

$$rc_{pc} = a_c (1 / (\sum |c| + \sum |r|) \sum_{r \in R} \sum_{t \in T} D_{ptr} \sum_{e \in E} PS_e CLS_{pce} \quad \forall p, c \tag{14}$$

$$rr_{pr} = \sum_{t \in T} D_{ptr} \sum_{e \in E} PS_e CLR_{pre} \quad \forall p, r \tag{15}$$

$$rr_{pr} \leq or_r M \quad \forall p, r \tag{16}$$

$$\sum_{c \in C} rc_{pc} + \sum_{r \in R} rr_{pr} = \sum_{v \in V} rp_{pv} \quad \forall p \tag{17}$$

$$rp_{pv} \leq ar_{pv} RCP_{pv} \quad \forall p, v \tag{18}$$

$$\sum_{p \in P} rp_{pv} \rho_{pi'} (1 - WS_{i'v}) = rz_{i'v} \quad \forall i, v \tag{19}$$

$$\sum_{v \in V} rz_{i'v} - \sum_{p \in P} \sum_{t=2} \sum_{k \in K} \sum_{r \in R} y_{ptkr} \rho_{pi'} + \sum_{s \in S} nz_{is} = \sum_{p \in P} \sum_{t=3} \sum_{k \in K} \sum_{r \in R} y_{ptkr} \rho_{pi'} \quad \forall i \tag{20}$$

$$\sum_{p \in P} \sum_{t=1} \sum_{j \in J} \sum_{k \in K} x_{ptjk} \rho_{pi} + \sum_{s \in S} nz_{is} = \sum_{s \in S} z_{is} \quad \forall i \tag{21}$$

$$z_{is} \leq zs_{is} CAS_{is} \quad \forall i \in I, s \tag{22}$$

$$zs_{is} \leq qa_s \quad \forall i, s \tag{23}$$

$$u_{pj} \leq qc_j \quad \forall p, j \tag{24}$$

$$\sum_{j \in J} u_{pj} \geq 2 \quad \forall p \tag{25}$$

$$\sum_{s \in S} zs_{is} \geq 2 \quad \forall i \tag{26}$$

$$ak_{kr} \in \{1,0\}, \forall k, r; u_{pj} \in \{1,0\}, \forall p, j; po_{mcrr1} \in \{0,1\}, \forall m, c, r, r1; w_{pk} \in \{1,0\}, \forall p, k; a_c \in \{1,0\}, \forall c; \; or_r \in \{0,1), \forall r; ar_{pv} \in \{1,0\}, \forall p, v; zs_{is} \in \{1,0\}, \forall i, s; qc_j \in \{1,0\}, \forall j; \tag{27}$$

$$D_{ptr}, x_{ptjk}; y_{ptkr}; z_{is}; rz_{i'v}; rc_{pc}; rr_{pr} \quad \text{integers} \tag{28}$$

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 po_{mcrr1} 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 (t = 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 $qa_{s.}$ 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 qc_j 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\$74.99 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 secondhand 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.

Table 2 Illustration of model parameters and decision variables for three example SC Cases

Supply Chain Cases	**1**	**2**	**3**
Products	7	9	6
Inputs	22	24	16
Model Outputs			
Profit $M	36.9	50.79	26.35
Revenue $M	116.15	174.62	74.99
Penalty $M	11.15	12.73	6.55
Total SC cost (TC)	79.25	123.73	48.65
Input Basis			
Average price in $	143.5	143.10	142.6
Total demand (all product)	510,338	862,521	381,382
Market	5	6	4
Retailer	12	14	10
Allocated **Plants**	6	7	4
Model decision: u_{pj}=1; *p*: product allocated to plant *j*; *u*(1,1)=1 means Product 1 allocated plant1	Product to (Plants) 1(3,5,6); 2(2,5,6); 3(2,3,4);4(3,4,6); 5(1,4,5); 6(3,4,6); 7(1,5,6)	Product to (Plants) 1(1,4,5); 2(2,35); 3(4,6,7); 4(1,3,4); 5(1,2,6); 6(2,6,7); 7(1,4,6);8(3,4,5); 9(,3,5,6)	Product to (Plants) 1(1,4); 2(2,3); 3(2,3);4(1,3); 5(1,4); 6(1,3);
Allocated DCs to **retailers**	5	7	7
Model decision $ak_{k\ r}$ = 1, (DC) *k* is allocated to distribute product to retailer *r*; so *ak* (1,1) =1 stands for: retailer 1 is allocated DC 1	Retailer (allocated DCS) 1(1,2); 2(1,2); 3(1,4); 4(3,5); 5(4,5); 6(3,5); 7(1,2); 8(2,3); 9(1,5); 10(2,3); 11(4,5);12(1,4)	Retailer(allocated DCs): 1(2,3); 2(5,7); 3(6,7); 4(1,7); 5(1,5);6(4,6); 7(1,6); 8(2,6);9(5,7); 11(2,7);12(4,5); 13(4,6); 14(1,7)	Retailer (allocated DCs): 1(1,2); 2(1,7),3(3,7);4(1,5); 5(2,3); 6(2,3); 7(3,7);8(5,6); 9(3,7);10(5,6)
Assigned orders to **suppliers**	11	6	5
Model decision on assignment of input order to Suppliers: za_{is} =1; if component *i* ordered to supplier s; *za*(1,1)=1 means order for input 1 is assigned to supplier 1	Component to (suppliers) 1(4,10);2(3,5);3(6,7); 4(4,9); 5(7,9); 6(5,7); 7(3,11); 8(6,10); 9(1,11); 10(2,9); 11(3,10); 12(1,2); 13(7,9); 14(5,9); 15(6,9); 16(3,10); 17(2,6); 18(5,7); 19(2,7); 20(10,11); 21(8,10); 2(2,71);	Component to (Suppliers) 1(2,6);2(3,4); 3(1,5); 4(3,5); 5(2,3); 6(3,5); 7(2,3); 8(4,5). 9(2,4) 10(1,4); 11(2,6),12(2,5); 13(1,3); 14(2,3,4,6) 15(4,6); 16(2,6); 17(2,4); 18(1,3),19(2,4); 20(3,4), 21(4,6); 22(4,5);23(2,3); 24(1,4)	Component to (suppliers) 1(1,2);2(2,4,5); 3(3,4); 4(1,2,4), 5(3,5); 6(1,3); 7(3,4); 8(2,3,5); 9(2,4); 10(2,3,5); 11(1,3,4); 12(1,5); 13(3,4,5); 14(2,4,5); 15(2,4); 16(2,5)
SCOCs Planned	6	7	7
Model decision on opening SCOC *c*, *po*(*m*,*c*,*r*1, *r*2)=1 if SCOC (c) is opened in market *m* between retailers r and r1, the if distance between retailers *r1* and *r2* exceed set distance limit *DSL*	SCOC (retailer pair) *Market 1: 1 (2,12); 2(10,11); * *Market 2: 1(1,11); 2(7,8); 3(9,12); Market3: 1(10,12); 2 (2,11); Market 4: 1(11,12); Market 5: 1(2,11); 3(10,12);	SCOC (retailer pair) Market 1: 0 ; Market 2: 0 ; Market3: 1(4,8); Market 4: 1(3,12); 3(5,10); 4(2,13); Market5:1(2,7); 3(2,6); 5(4,11); Market 6: 0	SCOC (retailer pair): Market1: 1(3,4); 3(2,5);5(4,5); Market2:0CH; Market 3:0 CH; Market 4: 1(1,6); 5(2,3);
Details on * and ** are shown in Appendix **Table 1.1** and Appendix **Table 1.2**			
Assigned **RSPs for Recovery**	6	7	6

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 and3 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. For example, 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 set the 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}.

Table 3 Typical component used by products 1,2, and 3 of SC cases 1,2, and 3

	SC case 1	SC Case 2	SC case 3
Product	Component use	Component use	Component use
1	2,4,5,8,9,10,12,14,16,17,18	2,3,6,8,10,11,12,14,17,20,21,22	2,4,5,7,8,10,13,14
2	5,6,7,8,9,11,12,13,17,20,21,22	2,6,7,13,14,17,20,22,24	1,3,4,6,9,10,13,16
3	3,6,7,8,10,12,14,15,17,19,21,22	1,4,5,8,9,11,14,16,17,18,20,21,24	1,4,6,9,10,11,12,15

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 4.a**. Based on **Table 4.a**, demand for new product 1 from retailer 1 is 5,551; **Table 4.a** 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**.

Table 4 New, remanufactured and second-hand product realized by the SC cases

Manufacturing of Products	1	2	3	4	5	6	7	8	9
SC Case 1									
New	71,491	84,622	75,097	70,082	59,588	81,898	67,560		
Remanufactured	50,203	59,624	51,679	47,727	40,720	58,464	45,309		
Secondhand	20,997	25,896	22,472	21,735	16,971	24,902	19,576		
SC Case 2									
New	113,786	73,616	106,130	95,186	99,747	99,882	71,968	86,709	115,497
Remanufactured	88,497	44,523	61,778	61,419	56,381	59,470	41,265	49,044	63,716
Secondhand	13,241	6,505	9,170	9,800	8,776	8,688	5,758	8,030	9,038
SC Case 3									
New	64,885	61,745	66,375	63,950	60,352	64,075			
Remanufactured	36,616	42,910	42,398	38,128	41,212	35,077			
Secondhand	8,434	10,464	9,992	8,167	8,513	8,408			

Table 4.a 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	Products								
	1	2	3	4	5	6	7	8	9
SC Case 1									
By retailers	42,510	51,471	44,534	41,648	35,067	50,023	39,410		
By SCOCs	14,174	17,184	14,850	13,815	11,738	16,623	13,167		
SC Case 2									
By retailers	63,605	37,195	52,317	48,939	49,505	49,411	35,023	42,345	55,376
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			

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.

SC2: 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_{pce} 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+ 0.24*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 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.

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

SC Case 1				SC Case 2				SC Case 3			
CN	Quantity	CN	Quantity	CN	Quantity	CN	Quantity	CN	Quantity	CN	Quantity
1	104,137	13	214,714	1	178,166	13	283,305	1	206,008	13	80,507
2	102,818	14	209,586	2	291,393	14	416,279	2	83,266	14	119,966
3	201,785	15	161,444	3	215,295	15	72,224	3	121,609	15	79,084
4	98,561	16	202,772	4	130,137	16	192,931	4	161,734	16	82,464
5	211,346	17	315,853	5	306,692	17	358,300	5	116,797		
6	216,780	18	150,161	6	423,645	18	394,063	6	84,894		
7	273,504	19	101,120	7	110,892	19	158,507	7	157,242		
8	263,145	20	216,845	8	199,998	20	427,642	8	40,078		
9	270,633	21	217,079	9	232,492	21	319,090	9	126,101		
10	151,357	22	216,640	10	212,093	22	347,483	10	201,523		
11	150,438			11	192,410	23	106,854	11	122,568		
12	304,374			12	319,756	24	279,031	12	85,027		

Table 7 presents overall energy spent in MJ and the generated harmful emissions in equivalent CO_2 in the manufacturing and remanufacturing of products; realizing new components from suppliers; component recovery; and transportation and distribution of products by the SC Cases 1,2 and 3, as estimated by the model. For example, SC Case 1 spent 14.44 million MJ of energy and generated 5.19 million kgs of CO_2 equivalent emission for manufacturing and remanufacturing products (**Table 7**). Similar data for the three 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 CO_2 (CATF, 2009; NGHAF, 2013).

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

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 CO_2 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 the collection of returns component recovery and reuse, and cost optimization, in addition to LCA metrics for spent energy and harmful emissions.

Model output for the transportation of typical products from production plants to DCs is presented in Appendix **Table 3.1.** Typical distribution of product from DCs to the retailer for 4 products involving 2 SC cases are presented in Appendix **Table 2.1** and **Table 2.2**. We illustrated the 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	95	0	115	94	91	89	91	63	86	67	88	120
3	93	115	0	62	89	65	79	110	83	77	84	90
4	65	94	62	0	105	78	68	81	88	68	85	72
5	76	91	89	105	0	77	74	79	92	91	78	75
6	83	89	65	78	77	0	98	62	73	99	78	92
7	103	91	79	68	74	98	0	78	107	75	68	90
8	96	63	110	81	79	62	78	0	71	81	97	84
9	92	86	83	88	92	73	107	71	0	89	104	92
10	66	67	77	68	91	99	75	81	89	0	120	96
11	78	88	84	85	78	78	68	97	104	120	0	69
12	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	98	94	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 case1.

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						533		6,503				
4			12,397		12,469							12,234
5				11,920		11,292			11,008		12,083	
SC Case 1	**Product 5**											
	Retailer											
DCs	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	10,214		10,020				4,194					9,572
2		9,576					5,094			9,260		
3								9,918	4,354			
4					9,529							
5				9,992		10,201			5,643		9,712	

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	**Product 1**										
	Retailer										
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									16,195	16,428	
5		3,677									
7		9,892	16,546				15,613	16,183			
SC Case 2	**Product 2**										
	Retailer										
DCs	1	2	3	4 to 7	8	9	10	11	12	13	14
2	9,467				8,403			8,046			
3							8,090				
4						8,953			8,785		8,563
5		8,414									
7			9,108				274	1,128		9,334	

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 ak_{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

	Distribution center or DCS					
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 **Table3.1** 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 an example 14,837 product 3 have been transported from the production plants to DC 1, as may be observed I Appendix **Table 3.1.**

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