Modelling of sharing networks in the circular economy

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Abstract

Purpose – The purpose of this paper is to develop and optimize a mathematical model based on a framework that integrates key concepts related to a circular economy (CE) and sharing economy (SE) for a leading manufacturer of laptops in India.

Design/methodology/approach – This study mathematically modelled the integration of sharing networks in a circular production system. This is done through an optimization package that deploys a multi-objective mixed-integer linear programming model.

Findings – This study evaluated the economic benefit and the environmental impact associated with the aforementioned integration in a production system. This study illustrated the inverse relationship between economic benefit and environmental impact and provided a set of solutions that can be used according to the case organizations goals, capacities and logistical capabilities.

Research limitations/implications – This study will aid similarly structured companies in adopting this approach to integrate sustainable practices in their production system. It also enumerated Industry 4.0 (I4.0) use-cases that can be used to effectively implement this mathematical model. Further research can be conducted using multiple companies in an inter-dependent network to maximize synergy.

Practical implications – This study will help to better understand the role of sharing networks in the circular economy model especially in the consumer electronics industry.

Originality/value – This study is the first of its kind to mathematically model the integration of aspects related to SE and CE. It also validates the aforementioned model using a numerical case-study and offers decision-support to key executives within the case organization.

Keywords Circular economy, Sharing networks, Sustainable production, Multi objective mixed-integer linear programming, Network design, Industry 4.0, Optimization, Modelling, Sensitivity, Circular economy

Paper type Research paper

Introduction

Rapid industrialization has witnessed massive development in extracting, processing and manufacturing units. The manufacturing organizations have focussed on value creation through the maximization of production and sale and have neglected their focus on the environmental impact of their operations (Lieder *et al.*, 2017). To keep up with social and corporate trends, industries are facing upward pressure to ensure sustainability in their production and distribution operations (Tseng *et al.*, 2018). Even though multiple ecological

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and economic theories have stressed the adverse anthropological impact of production infrastructures, the sector is sluggish to react (Beamon, 1999). Keeping this in mind, various supply-chain management theories have emphasized on the minimization of the negative impact of production systems on the environment (Pishchulov *et al.*, 2018). However, it is quite difficult for industrialists and top-level management executives to prioritize the environmental paradigm, as well as thrive economically, especially in a hyper-capitalist landscape, with stiff competition making it all the more difficult (Genovese *et al.*, 2017).

The main focus of this research is to provide comprehensive and holistic approach is to reconcile the inherent trade-off between economic utility and environmental impact to reach an optimal compromise solution through efficient network design that integrates forward (FL) and reverse logistics (RL). This novel attempt aims to integrate facets of a sharing economy (SE) such as sharing networks into a conventional circular production system, in such a way that economic benefits do not outweigh environmental conservation. The secondary objective of this research study is to thoroughly investigate the supply-chain landscape to conceptualize a framework that leverages technological tools and practices associated with Industry 4.0 (I4.0) to aid key stakeholders in achieving sustainability in this integrated economy. This research study aims at:

- Analyzing organizations that have attempted to quantify economic, environmental and social objectives in the context of production.
- Integrating sharing networks in a circular production system to mathematically model multiple objective (economic, environmental and social) functions in an explicit, distinct and disaggregated manner.
- Developing a mathematical model that uses multi-objective mixed-integer linear-programming (MOMILP) to analyze the production system and to optimize the model using a non-negative weighted-sum scalarizing function.
- Developing a framework that outlines the use-cases of tools and technologies associated with I4.0 to achieve a transition to this integrated economy.
- Curate economic, social and environmental policy implications to incentivize transitions to this integrated economy.

The study focusses upon quantifying and optimizing the aforementioned objectives of a leading Indian consumer electronics manufacturer. The study also outlines the implementation pathways for the proposed model with the innovative I4.0 technologies available.

The following subsections talk about the relevant literature reviewed to carry out this study, the methodology adopted, a mathematical model developed by elucidating its nuances. Followed, by the numerical validation and discussion of results based on the simulation and mapping the transition to CE based on the I4.0 tools and techniques. The last sections include the key theoretical, practical, managerial, social and environmental implications of this study by highlighting the objectives addressed in this study underlining the future scope and limitations of this study reported.

Literature review

Literature was examined in the perspective of better understanding the relevance of concepts such as the circular economy (CE), sharing economy (SE), and on how radical technologies and tools of I4.0 can be used for successful implementation by other researchers.

Circular economy

The theories associated with a CE aims to effectively target the environmental sustainability of production systems through the reuse of materials across multiple industries (Amin and Zhang, 2012). This not only has the benefit of conserving the environment but also increasing the value-added through refining the material streams. This approach focusses on three principles, namely, reduction of waste and pollution, reuse of materials and products and regeneration of natural systems (Ellen MacArthur Foundation, 2016). There is also a heavy emphasis on the maximization of the system's positive impact through industrial symbiosis and innovative change (Energy Crossroads, 2017). The model designates consumption in biological cycles and restoration in technological cycles. Closed-loop practices designate the movement of used/disposed of products back to the original manufacturer (Savaskan *et al.*, 2004). This is not only linked to a single manufacturer but also a network of manufacturers across multiple industries who may have use-cases for the parts and/or material gained from the returned product (Chertow, 2008). However, the supply-chain transitions from a linear economy to a circular one have its own unique challenges (Lieder and Rashid, 2016). It does not amount to a simple conversion but a systematic shift that aims at restoring the environment, generating economic and business opportunities, building long-term resilience and reinforcing social benefits (Ritzén and Sandström, 2017).

Sharing economy

The theories associated with a SE aims to effectively target economic and collaborative sustainability of production systems through various forms of peer-to-peer (P2P) exchange that is facilitated through community-based platforms (Business Model Toolbox, 2017). This approach focusses on increasing the effective use of under-used and/or barely-used resources through sharing activities (Richardson, 2015). This practice is heavily strengthened in the wake of rapid digitization of economic practices that include but are not limited to access to the internet, resource-metering tools and an increase in online communication (Wang *et al.*, 2019). Even though it seems like this practice might hurt industrialists and corporations, the advantages of serving an economic sector completely while using lesser resources and energy for production are enticing to one and all (Möhlmann, 2015). In this regard, manufacturers can charge higher premiums to businesses and high-frequency users (those that may share) for high-durability products while subsidizing the low-frequency users (personal use) through contracts.

Industry 4.0

The rapid digitalization of industrial technology paved the way to a transformational platform that the study refers to as I4.0. I4.0, in many ways, simplifies and strengthens core areas of industrial technology such as data collection and analysis across production systems, faster and flexible process control and automation algorithms (smart factories) that are capable of handling entire plants (De Sousa Jabbour *et al.*, 2018). While consumer behaviour and dynamics play a critical role in the transition from a linear economy to an integrated CE/SE. The industries often underplay the role of technological disruptions in this process of transformation (Antikainen *et al.*, 2018). Various tools and technologies such as internet-of-things (IoT), robotics, blockchain, Big Data, automation and additive manufacturing are just waiting to be exploited in the context of CE/SE (Euromonitor International, 2017). This is clearly a saddle-point between CE/SE and I4.0 that can be leveraged through innovative and novel use-cases that can enable, implement, and eventually, sustain the required transition (Pagoropoulos *et al.*, 2017).

Literature gap identified

An industry or business is only as effective as the design of its supply-chain network. This aspect of supply-chain planning (SCP) takes into consideration an end-to-end model that includes all facets of procurement, manufacturing and distribution of finished products (Ko and Evans, 2007). It is essential to recognize the strategic role that RL plays in this aspect, as it is vital to design infrastructural capabilities and routes to handle the projected high-volume of product returns, which will only increase in the future (Srivastava, 2008). Even though India is one of the leading developing countries with respect to manufacturing infrastructure, the role of RL is under-rated in the current context. The industry must, hence, understand that the lifetime value in conceptualising a robust and reliable RL will pay dividends not only with respect to cost-savings but also with respect to maintaining the integrity of the environment by minimizing our carbon footprint (Otto and Kotzab, 2003). In this study, a novel attempt have been made to integrate aspects of CE and sharing networks such as collection centres, refurbishment centres, and sharing hubs in the existing linear supply chain model, which was not attempted by researchers earlier.

Methodology

The methodology adopted in the study reported is presented in Figure 1.

The study starts with the understanding of existing mathematical models such as the single objective, multiple objectives, single integer and multi integer models. MOMILP was preferred to handle two objectives at the same time. A mathematical model was developed based on the indices, parameters, decision variables, objective functions and constraints conceived from the literature and real-time sources. The model developed was checked for its feasibility of adoption in our case organization based on their request and requirement. Data related to product specification, component, transport parameters, revenue and cost details, limitations and goals of the organizations were collected and the model was numerically simulated using GAMS and validated using CPLEX.

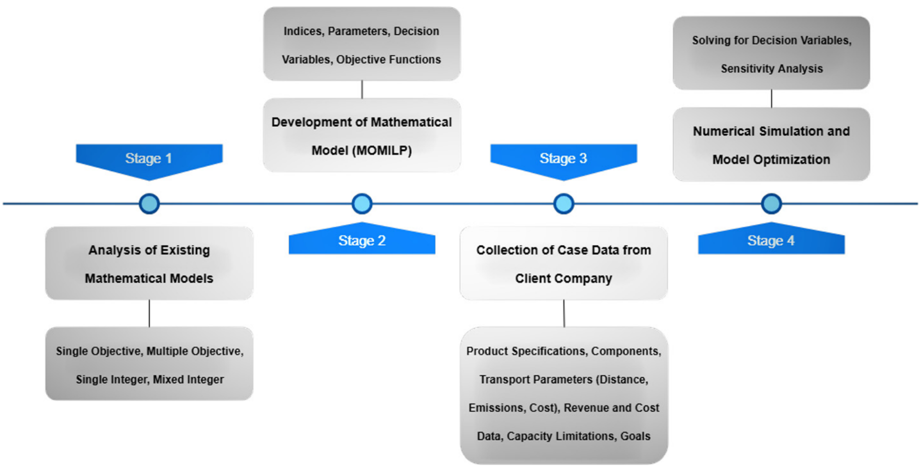

Figure 1.
Flowchart of methodology adopted

Mathematical modelling

The mathematical model developed, indices, parameters, decision variables, objective functions, constraints used and solving methods adopted in this study are discussed in this section.

Multi-objective mixed-integer linear-programming

This study shall use a multi-objective linear-programming model as opposed to a single-objective linear-programming model as this study looks to optimize two objective functions in a simultaneous manner, namely, the economic utility and the environmental impact. In this regard, this study explicitly and distinctly considers the aspects associated with both the objective functions as opposed to aggregating those aspects into a unified economic objective function. In these mathematical models, it is not possible to find a one-size-fits-all optimal solution as an optimization in one objective function is not possible without a sacrifice in another objective function, eventually giving rise to non-dominated solutions (Antunes *et al.*, 2004).

The inherently conflicting nature of both these objective functions is further evaluated as a trade-off analysis that provides the decision-makers with suitable decision support (Agarwal *et al.*, 2011). The decision-makers can then consider this analysis in light of their priorities and expectations to select a compromise solution from the set of non-dominated solutions (Gomes da Silva *et al.*, 2006). The effective objective function is a scalarized form of a positive weighted-sum of the aforementioned objective functions, which when optimized, yields the required non-dominated solutions according to the constraints and the data that are provided (Torabi and Hassini, 2008).

General algebraic modelling system

The general algebraic modelling system (GAMS) is a technological system, which is used for optimization of mathematical functions. GAMS can be used to custom-model and solve various mixed-integer linear problems in SCP operations. Moreover, it is designed to handle large datasets and complex networks, which are essential in this study reported. It also provides access to a plethora of mathematical solvers and engines out of which this study shall be using the CPLEX 12.8 and the XPRESS 33.01 solvers.

CPLEX 12.8, provided by IBM ILOG, is designed to decompose high-level mixed-integer problems into multiple subproblems, which are then solved using the branch-and-cut algorithm. XPRESS 33.01, provided by FICO, combines the power of a simplex-based solver and a mixed-integer module. This solver uses the branch-and-bound algorithm to search for an optimal solution based on a set of criteria that includes computation time, constraint resolution and the number of nodes explored. This study shall cross-check the solution obtained through the CPLEX 12.8 solver with the XPRESS 33.01 solver to check for consistency in programming methodology and the reliability of the solution obtained.

Proposed framework

The proposed framework can be divided into the following two parts: the design of the circular production system with the linkage of a sharing network; and the geographical model of the aforementioned system in a numerical case study to evaluate the feasibility and the robustness of the mathematical framework.

In a conventional (linear) production system, the suppliers supply the manufacturer with the required amount of new parts (fresh parts) for the manufacture of new products, where the production capacity of the suppliers (Gou *et al.*, 2016) and the demand forecasts (Cachon and Lariviere, 2001) play a vital role. The manufacturer then sends the new products to a

Sales and Distribution (S&D) network that consists of wholesalers, retailers and resellers. The S&D network then pushes the products to a customer network that consists of businesses, non-commercial groups and individuals. The customer network then disposes of the products after their intended usage.

However, in the proposed framework (Figure 2) the S&D network has the capability to resell used products to the customer network along with the new products. The customers purchase these products according to either a conventional end-user model or a return-after-usage model. The customers then have the option to deposit their used products at Inspection and Collection (I&C) centres, which inspect and segregate the products into two categories, namely, usable and defective products.

The usable products are either sent back to the S&D network for resale or sent to sharing hubs, which repair and share the products with the customer network in a customer to customer, business to customer or business to business format. The defective products and the end-of-lifecycle products deployed at sharing hubs are now sent to reprocessing centres, which disassemble and segregate the parts into two categories: usable and defective parts. The usable parts are refurbished and sent back to the manufacturer for the manufacture of new products while the defective parts are sent to recycling centres, where they are subject to recycling processes for the extraction of usable raw material (Zhang *et al.*, 2018). The raw material extracted from the defective parts is then sent to suppliers for the manufacture of new parts.

As this framework follows a methodical approach that follows an RL network to replenish the different nodes in the supply chain, it is inherently designed to uphold the core principles and practices associated with a CE and/or SE. The novelty of this approach lies in the fact that aspects of a SE are now effectively integrated into a CE. This framework will now be numerically evaluated to provide quantifiable incentives to manufacturers to transition to an integrated economy that includes CE and SE networks.

Model description

The mathematical model that this study considers expresses the various components of the proposed framework in terms of indices, parameters and decision variables to mathematically evaluate the economic utility and environmental impact of activities

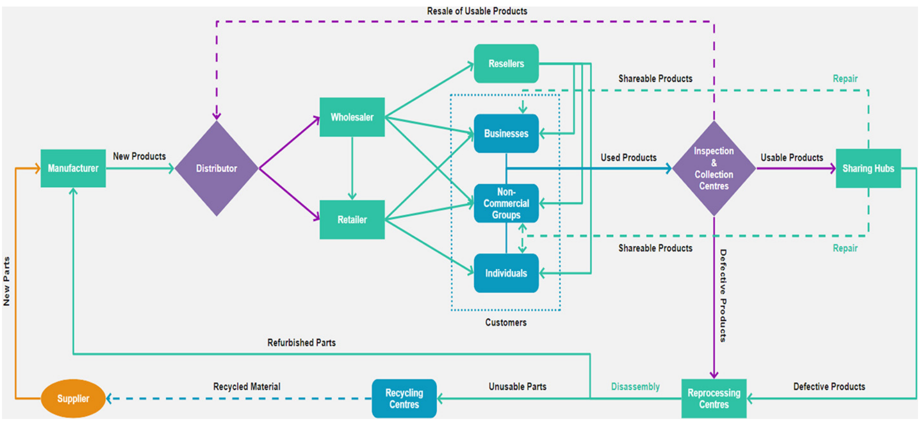

Figure 2.
Design of a circular production system with sharing networks

associated with the supply chain. This mathematical model is derived from the model developed in an earlier study that analysed the network design for a circular production system using a MOMILP model (Vimal *et al.*, 2018). The mathematical model is based on the following assumptions:

- The maximum capacities of the suppliers, manufacturer, I&C centres, sharing hubs, reprocessing centres and recycling centres are quantifiable on a product and/or part level and are known.
- The market demand can be forecasted in an accurate and reliable manner on a product level. The market-demand for new products cannot simply be met by the inflow of refurbished parts alone. Parts have to be purchased from an external supplier at all times.
- The service-life variation between products produced from new parts and those produced from refurbished parts is negligible.
- The costs associated with the inspection, collection, repair, sharing, disassembly, refurbishment, recycling and transport are quantifiable on a product and/or part level and are known.
- The variation in costs and/or revenues attached to various products and/or parts within the same product line and/or part line is negligible. The variation in fixed costs associated with the establishment and running of various facilities on a product and/or part level within the same facility line is negligible. The variation in monetary costs associated with transport on a product and/or part level within the same route is negligible. The variation in pollution costs associated with transport on a product and/or part level within the same route is negligible.
- The aggregation of revenue associated with the sharing route is more than that associated with the reprocessing route. The aggregation of costs associated with the reprocessing route is lesser than that associated with purchasing new parts. The aggregation of costs associated with the recycling route is lesser than that associated with sourcing fresh raw material.
- The mathematical model is that of a single-period.

Indices

Indices are those quantities that are quantifiable and are unique to each numerical case. They form the foundation of our mathematical model and do not change over the reference period of our simulation. The variables associated are listed in Table I.

Table I. List of indices

Variable	Function
A	Array of parts, $a = 1, 2, \ldots, A$
B	Array of products, $b = 1, 2, \ldots, B$
C	Array of suppliers, $c = 1, 2, \ldots, C$
I	Array of S&D centres, $i = 1, 2, \ldots, I$
J	Array of I&C centres, $j = 1, 2, \ldots, J$
k	Array of sharing hubs, $k = 1, 2, \ldots, K$
L	Array of reprocessing centres, $l = 1, 2, \ldots, L$
M	Array of recycling centres, $m = 1, 2, \ldots, M$

Parameters

Parameters are those quantities that are easily quantifiable and are common to multiple sub-industries within the realm of production. They vary according to factors including but not limited to supplier-competency, manufacturer-efficiency, market-forces and third-party providers. The variables associated are listed in Table II.

Decision variables

Decision variables are those quantities that are to be optimized in accordance with the objective functions. They are chosen carefully to include only those quantities that can be controlled in a practical environment. The variables associated are listed in Table III.

Objective functions

Equation (1) expresses the first objective function that maximizes economic utility. The terms associated with this function are expressed in Table IV.

$$
\begin{aligned}
\boldsymbol{Z}_1 = {} & \sum_{b=1}^{B}\left\{((SP_b - CP_b)\times X_b) + \sum_{k=1}^{K}(R3_{bk}\times Z_{bk})\right\} + \sum_{a=1}^{A}\sum_{l=1}^{L}\{R1_{al}\times Q_{al}\} \\
& + \sum_{a=1}^{A}\sum_{m=1}^{M}\{R2_{am}\times R_{am}\} - \sum_{a=1}^{A}\sum_{c=1}^{C}\{C3_{ac}\times S_{ac}\} \\
& - \sum_{b=1}^{B}\sum_{i=1}^{I}\sum_{j=1}^{J}\{PC1_{bj}\times Y_{bij}\times Col_b\} - \sum_{b=1}^{B}\sum_{k=1}^{K}\{PC2_{bk}\times Z_{bk}\times Sha_b\} \\
& - \sum_{a=1}^{A}\sum_{l=1}^{L}\{PC3_{al}\times P_{al}\} - \sum_{a=1}^{A}\sum_{l=1}^{L}\{PC4_{al}\times Q_{al}\times Ref_a\} \\
& - \sum_{b=1}^{B}\sum_{i=1}^{I}\sum_{j=1}^{J}\{TL1_{bij}\times Y_{bij}\} - \sum_{b=1}^{B}\sum_{j=1}^{J}\sum_{k=1}^{K}\{TL2_{bjk}\times Z_{bk}\} \\
& - \sum_{b=1}^{B}\sum_{j=1}^{J}\sum_{l=1}^{L}\{TL3_{bjl}\times W_{bl}\} - \sum_{b=1}^{B}\sum_{k=1}^{K}\sum_{l=1}^{L}\{TL4_{bkl}\times Z_{bk}\} - \sum_{a=1}^{A}\sum_{l=1}^{L}\{TL5_{al}\times Q_{al}\} \\
& - \sum_{a=1}^{A}\sum_{l=1}^{L}\sum_{m=1}^{M}\{TL6_{alm}\times R_{am}\times Rec_a\} - \sum_{b=1}^{B}\sum_{j=1}^{J}\{EC1_{bj}+FC1_{bj}\} \\
& - \sum_{b=1}^{B}\sum_{k=1}^{K}\{EC2_{bk}+FC2_{bk}\} - \sum_{a=1}^{A}\sum_{l=1}^{L}\{EC3_{al}+FC3_{al}\} - \sum_{b=1}^{B}\sum_{k=1}^{K}\{C1_b\times Z_{bk}\} \\
& - \sum_{b=1}^{B}\sum_{l=1}^{L}\{C2_b\times W_{bl}\}
\end{aligned}
\tag{1}
$$

Equation (2) expresses the second objective that function minimizes environmental impact. The terms associated with this function are expressed in Table V.

Variable	Function
Dem_b	Average demand for the product *(b)*
Cap_b	Maximum capacity of the manufacturer for the product *(b)*
SP_b	Average selling price of a product *(b)*
CP_b	Average cost price of a product *(b)*
PP_{ab}	Number of parts *(a)* used to produce a product *(b)*
$TL1_{bij}$	Average cost to transport a product *(b)* from an S&D centre *(i)* to an I&C centre *(j)*
$PC1_{bj}$	Average cost to acquire a product *(b)* at an I&C centre *(j)*
$EC1_{bj}$	Average fixed cost to establish an I&C centre *(j)* to acquire a product *(b)*
$FC1_{bj}$	Average fixed cost to run an I&C centre *(j)* to acquire a product *(b)*
$Cap1_{bj}$	Maximum capacity of an I&C centre *(j)* for the product *(b)*
$TL2_{bjk}$	Average cost to transport a usable product *(b)* from an I&C centre *(j)* to a sharing hub *(k)*
$PC2_{bk}$	Average cost to repair a product *(b)* at a sharing hub *(k)*
$EC2_{bk}$	Average fixed cost to establish a sharing hub *(k)* to repair a product *(b)*
$FC2_{bk}$	Average fixed cost to run a sharing hub *(k)* to repair a product *(b)*
$Cap2_{bk}$	Maximum capacity of a sharing hub *(k)* for the product *(b)*
$TL3_{bjl}$	Average cost to transport a defective product *(b)* from an I&C centre *(j)* to a reprocessing centre *(l)*
$TL4_{bkl}$	Average cost to transport a defective product *(b)* from a sharing hub *(k)* to a reprocessing centre *(l)*
$PC3_{al}$	Average cost to disassemble a part *(a)* at a reprocessing centre *(l)*
$PC4_{al}$	Average cost to refurbish a part *(a)* at a reprocessing centre *(l)*
$EC3_{al}$	Average fixed cost to establish a reprocessing centre *(l)* to reprocess a part *(a)*
$FC3_{al}$	Average fixed cost to run a reprocessing centre *(l)* to reprocess a part *(a)*
$Cap3_{al}$	Maximum capacity of a reprocessing centre *(k)* for the part *(a)*
$TL5_{al}$	Average cost to transport a refurbished part *(a)* from a reprocessing centre *(l)* to the manufacturer
$TL6_{alm}$	Average cost to transport a defective part *(a)* from a reprocessing centre *(l)* to a recycling centre *(m)*
$R1_{al}$	Average revenue gained from a refurbished part *(a)* at a reprocessing centre *(l)*
$R2_{am}$	Average revenue gained from a defective part *(a)* at a recycling centre *(m)*
$R3_{bk}$	Average revenue gained from a usable product *(b)* at a sharing hub *(k)*
$C1_b$	Average cost to reimburse customers for a usable product *(b)*
$C2_b$	Average cost to reimburse customers for a defective product *(b)*
$C3_{ac}$	Average cost to source a part *(a)* from a supplier *(c)*
$QM1_c$	Minimum quantity of order from a supplier *(c)*
$QM2_c$	Maximum quantity of order from a supplier *(c)*
$PL1_{bij}$	Average pollution cost to transport a product *(b)* from an S&D centre *(i)* to an I&C centre *(j)*
$PL2_{bjk}$	Average pollution cost to transport a usable product *(b)* from an I&C centre *(j)* to a sharing hub *(k)*
$PL3_{bjl}$	Average pollution cost to transport a defective product *(b)* from an I&C centre *(j)* to a reprocessing centre *(l)*
$PL4_{bkl}$	Average pollution cost to transport a defective product *(b)* from a sharing hub *(k)* to a reprocessing centre *(l)*
$PL5_{al}$	Average pollution cost to transport a refurbished part *(a)* from a reprocessing centre *(l)* to the manufacturer
$PL6_{alm}$	Average pollution cost to transport a defective part *(a)* from a reprocessing centre *(l)* to a recycling centre *(m)*
Col_b	Maximum percentage of product *(b)* collected
Sha_b	Maximum percentage of product *(b)* shared
Ref_a	Maximum percentage of part *(a)* refurbished
Rec_a	Maximum percentage of part *(a)* recycled

Table II. List of parameters

$$
\begin{aligned}
Z_2 = & \sum_{b=1}^{B}\sum_{i=1}^{I}\sum_{j=1}^{J}\{PL1_{bij} \times Y_{bij}\} + \sum_{b=1}^{B}\sum_{j=1}^{J}\sum_{k=1}^{K}\{PL2_{bjk} \times Z_{bk}\} \\
& + \sum_{b=1}^{B}\sum_{j=1}^{J}\sum_{l=1}^{L}\{PL3_{bjl} \times W_{bl}\} + \sum_{b=1}^{B}\sum_{k=1}^{K}\sum_{l=1}^{L}\{PL4_{bkl} \times Z_{bk}\} + \sum_{a=1}^{A}\sum_{l=1}^{L}\{PL5_{al} \times Q_{al}\} \\
& + \sum_{a=1}^{A}\sum_{l=1}^{L}\sum_{m=1}^{M}\{PL6_{alm} \times R_{am}\}
\end{aligned} \tag{2}
$$

Equation (3) expresses the effective objective function that converts the aforementioned objective functions into a single multi-objective function, following a global-criterion approach. W_1 and W_2 serve as priority values, ranging from 0 to 1, based on the case organizations requirements, taking into consideration the capacity limitations of the

Table III.
List of decision variables

Variable	Function
X_b	Amount of products *(b)* to be produced
Y_{bij}	Amount of products *(b)* to be collected at I&C centres *(j)* from S&D centres *(i)*
Z_{bk}	Amount of products *(b)* to be sent to sharing hubs *(k)*
W_{bl}	Amount of products *(b)* to be sent to reprocessing centres *(l)*
P_{al}	Amount of parts *(a)* obtained from disassembly at reprocessing centres *(l)*
Q_{al}	Amount of parts *(a)* to be refurbished at reprocessing centres *(l)*
R_{am}	Amount of parts *(a)* to be recycled at recycling centres *(m)*
S_{ac}	Amount of parts *(a)* to be sourced from suppliers *(c)*

Table IV.
Terms associated with Z_1

Term	Function
1.1	Profit gained from selling (production) and sharing products *(Variable)*
1.2	Profit gained from refurbished parts *(Variable)*
1.3	Profit gained from recycled parts *(Variable)*
1.4	Cost of acquisition of parts from suppliers *(Variable)*
1.5	Cost of inspection and collection of parts *(Variable)*
1.6	Cost of repairing and sharing products *(Variable)*
1.7	Cost of disassembling parts from products *(Variable)*
1.8	Cost of refurbishing parts *(Variable)*
1.9	Cost of transporting products from S&D centres to I&C centres *(Variable)*
1.10	Cost of transporting products from I&C centres to sharing hubs *(Variable)*
1.11	Cost of transporting products from I&C centres to reprocessing centres *(Variable)*
1.12	Cost of transporting products from sharing hubs to reprocessing centres *(Variable)*
1.13	Cost of transporting parts from reprocessing centres to manufacturer *(Variable)*
1.14	Cost of transporting parts from reprocessing centres to recycling centres *(Variable)*
1.15	Cost of establishing and running I&C centres *(Fixed)*
1.16	Cost of establishing and running sharing hubs *(Fixed)*
1.17	Cost of establishing and running reprocessing centres *(Fixed)*
1.18	Cost of reimbursement to customers for usable products *(Variable)*
1.19	Cost of reimbursement to customers for defective products *(Variable)*

facilities. This is then multiplied with the objective functions, Z_1 and Z_2, to deliver the final result. The terms associated with this equation are expressed in Table VI.

$$\boldsymbol{Z_{eff}} = W_1 \times \left\{ \frac{Z_{1\,max} - Z_1}{Z_{1\,max}} \right\} - W_2 \times \left\{ \frac{Z_{2\,max} - Z_2}{Z_{2\,max}} \right\} \quad (3)$$

Constraints. Equation (4), the demand-based constraint, ensures that the market demand for the product is met by the total number of products manufactured. Equation (5), the collection-of-products constraint, calculates the total number of products collected at each I&C centre from multiple S&D centres. Equation (6), the total-parts constraint, ensures that the total number of manufactured parts equal the summation of the parts that are purchased from the suppliers and the parts that are refurbished at reprocessing centres.

Equation (7), the sum-of-products constraint, ensures that the total number of collected products equals the summation of the products that are shared at sharing centres and the products that are sent to reprocessing centres. Equation (8), the disassembly-of-parts constraint, ensures that the total number of disassembled parts equal the summation of the parts that are refurbished at reprocessing centres and the parts that are recycled at recycling centres. Equation (9), the disassembly-of-products constraint, ensures that the total number of parts that are obtained after disassembly at the reprocessing centres equals the summation of parts in the products obtained at I&C centres.

$$Dem_b = X_b \quad \forall b \quad (4)$$

$$\sum_{j=1}^{J} Y1_{bj} = \sum_{i=1}^{I} \sum_{j=1}^{J} Y_{bij} \quad \forall b \quad (5)$$

$$\sum_{b=1}^{B} \{X_b \times PP_{ab}\} = \sum_{c=1}^{C} \{S_{ac}\} + \sum_{l=1}^{L} \{Q_{al}\} \quad \forall a \quad (6)$$

Term	Function
2.1	Pollution cost to transport products from S&D centres to I&C centres *(Variable)*
2.2	Pollution cost to transport products from I&C centres to sharing hubs *(Variable)*
2.3	Pollution cost to transport products from I&C centres to reprocessing centres *(Variable)*
2.4	Pollution cost to transport products from sharing hubs centres to reprocessing centres *(Variable)*
2.5	Pollution cost to transport parts from reprocessing centres to manufacturer *(Variable)*
2.6	Pollution cost to transport parts from reprocessing centres to recycling centres *(Variable)*

Table V. Terms associated with Z_2

Term	Function
3.1	Scalarization of the first objective function, Z_1
3.2	Scalarization of the second objective function, Z_2

Table VI. Terms associated with *Zeff*

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\{Y_{bij}\} = \sum_{k=1}^{K}\{Z_{bk}\} + \sum_{l=1}^{L}\{W_{bl}\} \quad \forall b \tag{7}$$

$$\sum_{l=1}^{L}\{P_{al} - Q_{al}\} = \sum_{m=1}^{M}\{R_{am}\} \quad \forall a \tag{8}$$

$$\sum_{l=1}^{L}\{P_{al}\} = \sum_{b=1}^{B}\sum_{i=1}^{I}\sum_{j=1}^{J}\{Y_{bij} \times PP_{ab}\} \quad \forall a \tag{9}$$

Equation (10), the supplier-capacity constraint, ensures that the total number of parts that are sourced from suppliers are within the capacity limits of the suppliers. Equation (11), the manufacturer-capacity constraint, ensures that the total number of products that are produced are within the capacity limits of the manufacturer. Equation (12), the I&C centre-capacity constraint, ensures that the total number of products that are collected are within the capacity limits of the I&C centres. Equation (13), the sharing hub-capacity constraint, ensures that the total number of products that are shared are within the capacity limits of the sharing hubs. Equation (14), the reprocessing centre-capacity constraint, ensures that the total number of parts that are reprocessed are within the capacity limits of the reprocessing centres.

$$QM1_c \leq \sum_{a=1}^{A}\{S_{ac}\} \leq QM2_c \quad \forall c \tag{10}$$

$$X_b \leq Cap_b \quad \forall b \tag{11}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} Y_{bij} \leq \sum_{j=1}^{J} Cap1_{bj} \quad \forall b \tag{12}$$

$$\sum_{k=1}^{K} Z_{bk} \leq \sum_{k=1}^{K} Cap2_{bk} \quad \forall b \tag{13}$$

$$\sum_{b=1}^{B}\sum_{l=1}^{L}\sum_{k=1}^{K}\{(W_{bl} + Z_{bk}) \times PP_{ab}\} \leq \sum_{l=1}^{L} Cap3_{al} \quad \forall a \tag{14}$$

Equation (15), the maximum-collection constraint, ensures that the maximum amount of products is collected at I&C centres. Equation (16), the maximum-sharing constraint, ensures that the maximum amount of usable products is shared at sharing hubs. Equation (17), the maximum-reprocessing constraint, ensures that the maximum amount of defective products is sent to reprocessing centres. Equation (18), the maximum-refurbishing constraint, ensures that the maximum amount of parts is refurbished at reprocessing centres. Equation (19), the maximum-recycling constraint, ensures that the maximum amount of parts is recycled at recycling centres.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} Y_{bij} \leq Col_b \times X_b \quad \forall b \tag{15}$$

$$\sum_{k=1}^{K} Z_{bk} \leq Sha_b \times \sum_{j=1}^{J} Y1_{bj} \quad \forall b \tag{16}$$

$$\sum_{l=1}^{L} P_{al} \leq \sum_{b=1}^{B}\sum_{l=1}^{L}\{W_{bl} \times PP_{ab}\} + \sum_{b=1}^{B}\sum_{k=1}^{K}\{Z_{bk} \times PP_{ab}\} \quad \forall a \tag{17}$$

$$\sum_{l=1}^{L} Q_{al} \leq Ref_a \times \sum_{l=1}^{L} P_{al} \quad \forall a \tag{18}$$

$$\sum_{m=1}^{M} R_{am} \leq Rec_a \times \sum_{l=1}^{L}\{P_{al} - Q_{al}\} \quad \forall a \tag{19}$$

Equation (20), the numerical constraint, serves as a numerical constraint to ensure that the general integer values of the decision variables stay positive and real.

$$X_b,\ Y_{bij}, Z_{bk}, W_{bl}, P_{al}, Q_{al}, R_{am}, S_{ac} \geq 0 \in I \forall a, b, c, i, j, k, l, m \tag{20}$$

Numerical validation

The developed model was validated in a consumer electronics industry. The consumer electronics industry is arguably one amongst the fastest-growing industries in India in terms of products and exports. The computer-hardware market forms a sub-sector of the consumer electronics industry, consisting of computers, accessories, storage devices and other peripherals. Our case organization is a leading manufacturer of consumer electronics in India, including but not limited to mobile phones, laptops, televisions, air-conditioners, sound-systems, power-banks and home automation solutions. The case organization enjoys a strong market share in the Indian sub-continent and is among the top-10 players worldwide in the mobile-phone market. Focussing on India, the case organization client sells around 30-million products through more than 100-thousand retail outlets, on an annual basis. However, the case organization struggles to consolidate market share in the laptop market, due to global competition and lack of appropriate marketing initiatives. The case organization is looking to revitalize this division of their company through state-of-the-art research and development (R&D), cutting-edge market research and robust supply chain networks. Regarding sustainability, the case organization has exhibited compliance with the national legislation passed by the Ministry of Environment and Forests, India, namely, the E-Waste (Management and Handling) Rules, 2011. Moreover, the case organization strives to source its raw-material through ethical practices and evaluates its suppliers along with the same metric. By 2025, the case organization envisions to incorporate a "zero-waste" philosophy across all its supply chain activities through an integrated FL and RL network that minimizes its carbon footprint. While the case organization has a robust network of suppliers, manufacturing plants and retail nodes, it has planned to retrofit some of its support and service centres into I&C centres, sharing hubs and reprocessing centres. This study shall evaluate the proposed MOMILP model in accordance with the data collected from the case organizations laptop division to effectively quantify the trade-off between economic utility and environmental impact to select an optimal compromise solution in line with the case organizations vision.

Case in focus. This study shall focus on the case organizations network of suppliers, manufacturing plants, retail nodes, support and service centres, remanufacturing facilities and recycling centres in the city of Chennai, Tamil Nadu. This study starts by visualising the network in control of the case organization, by means of ownership or third-party contracts, as shown in Figure 3. The product specifications (laptop, display, processor type, processor speed, memory, storage, audio, battery, weight, cost), component specifications (number of components needed to manufacture a laptop), transport parameters (distance between

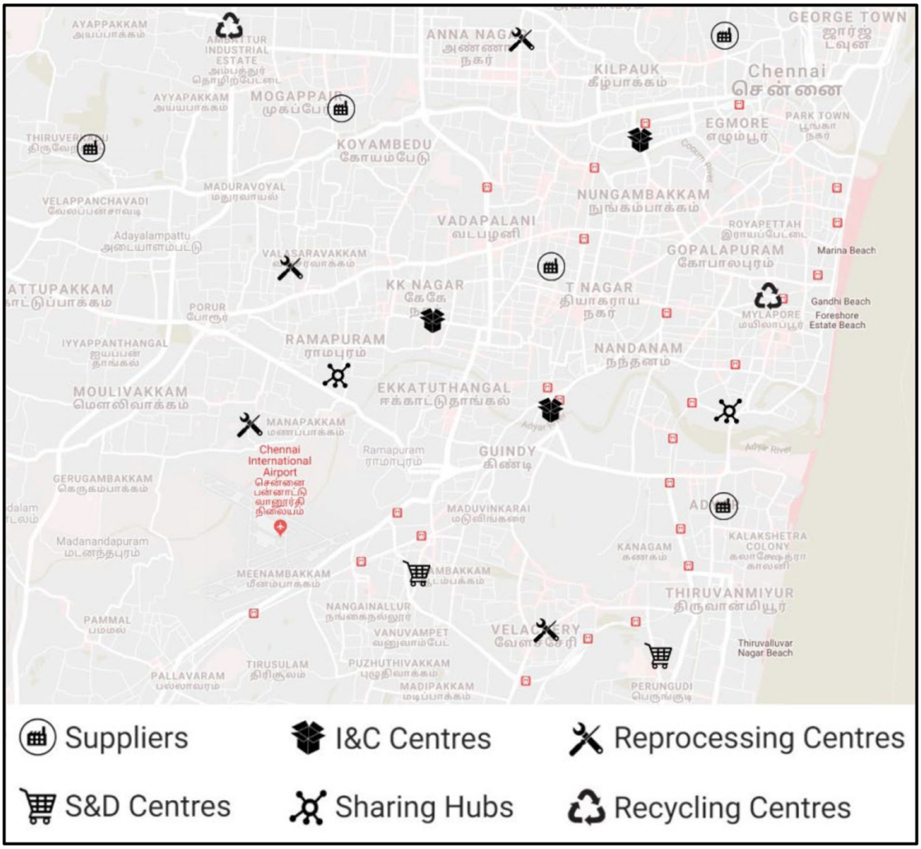

Figure 3.
Visualization of clients supply chain network

centres, emissions, cost) and centre parameters (revenue, cost, capacity) are key data considerations in this study. The variables are then populated within the list of indices in accordance with the aforementioned network possessed by the case organization (Figure 2) and are expressed in Table VII.

Data collection. The following information was collected through an integrated approach in which the first step involved the acquisition of production figures, sales data, market research and logistical data. The underlying data was then cleaned and analyzed using analytical toolboxes R-Studio and Tableau. Certain fields were populated through information collected from surveys and case studies of key stakeholders that were involved in the process. Data related to pollution was computed through a theoretical method as this study did not possess the capabilities to retrofit the logistical carriers with data-acquisition devices such as sensors. The amount of fuel consumed by the logistical carrier was estimated using mileage associated with various legs of the network and the average fuel economy exhibited by the logistical carrier, as depicted in equations (21) and (22).

$$Diesel\ Fuel\ (litres) = \frac{Mileage\ (kilometres)}{Fuel\ Economy\ (kilometres/litre)} \tag{21}$$

$$CO_2(kilograms) = Diesel\ Fuel\ (litres) \times 2.62\ kilograms/litre \tag{22}$$

However, this data was correlated with the carbon calculator provided by DHL Express, as shown in Figure 4. This calculator allows for the easy calculation and analysis of carbon footprint through interactive and dynamic form inputs that include route visualizations and shipment parameters. The emissions calculations follow an activity-based methodology to estimate the carbon footprint in accordance with multiple international protocols and standards (DHL Express, 2019). This data was then standardized and segregated on a per-

Table VII. Supply chain capabilities of the client

Variable	No. and type
Parts, *a*	5 (display, processing, storage media, audio system and battery)
Products, *b*	5 (Laptop 1, Laptop 2, Laptop 3, Laptop 4 and Laptop 5)
Suppliers, *c*	5 (storage and processing units, output units and power units)
S&D centres, *i*	2 (physical retail outlets, E-commerce websites)
I&C centres, *j*	3 (Drop inlet 1, Drop inlet 2, and Drop inlet 3)
Sharing hubs, *k*	2 (Computing hub 1 and Computing hub 2)
Reprocessing centres, *l*	4 (Service centre 1, Service centre 2, Service centre 3 and Service centre 4)
Recycling centres, *m*	2 (E-waste centre 1 and E-waste centre 2)

Source: DHL Express (2019)

Figure 4. Sample validation of carbon footprint calculations

product and/or per-part level according to the parameters that this study required. One monetary unit is equivalent to INR 100 and one pollution unit is equivalent to 1 kg of CO_2 emissions.

Table VIII numerically expresses the various parameters that are related to suppliers. Table IX numerically expresses the various parameters that are related to products. Table X numerically expresses the various parameters that are related to parts. Table XI numerically expresses the part-composition of each product, $\boldsymbol{PP_{ab}}$.

Table XII Numerically expresses the transportation-related costs to move products from S&D centres to I&C centres, $\boldsymbol{TL1_{bij}}$. Table XIII numerically expresses the transportation-

Table VIII. Supplier-related parameters

Parameter \ Supplier, c	*1*	*2*	*3*	*4*	*5*
$C3_{ac}$	21.00	14.00	8.50	5.00	3.25
$QM1_c$	500	2000	650	2000	3000
$QM2_c$	10,000	10,000	20,000	14,500	10,000

Table IX. Product-related parameters

Parameter \ Product, b	*1*	*2*	*3*	*4*	*5*
Dem_b	1,300	1,100	500	900	1,000
Cap_b	1,850	1,450	700	1,150	1,350
SP_b	150	210	180	105	130
CP_b	65.75	112.25	82.50	65.75	77.75
$C1_b$	29.60	50.50	37.10	29.60	35.00
$C2_b$	14.80	25.25	18.55	14.80	17.50
Col_b	0.55	0.55	0.55	0.55	0.55
Sha_b	0.40	0.40	0.40	0.40	0.40

Table X. Part-related parameters

Parameter \ Part, a	*1*	*2*	*3*	*4*	*5*
Ref_a	0.55	0.45	0.40	0.55	0.50
Rec_a	0.45	0.65	0.55	0.50	0.40

Table XI. Product-part composition, PPab

Part, a \ Product, b	*1*	*2*	*3*	*4*	*5*
1	1	2	1	1	2
2	2	3	2	2	1
3	1	1	2	1	1
4	1	2	2	1	2
5	1	3	2	1	1

related costs to move products from I&C centres to sharing hubs, $\boldsymbol{TL2_{bjk}}$. Table XIV numerically expresses the transportation-related costs to move products from I&C centres to reprocessing centres, $\boldsymbol{TL3_{bjl}}$. Table XV numerically expresses the transportation-related costs to move products from sharing hubs to reprocessing centres, $\boldsymbol{TL4_{bkl}}$. Table XVI numerically expresses the transportation-related costs to move parts from reprocessing centres to the manufacturer, $\boldsymbol{TL5_{al}}$. Table XVII numerically expresses the transportation-related costs to move parts from reprocessing centres to recycling centres, $\boldsymbol{TL6_{alm}}$.

Table XVIII Numerically expresses the pollution-related costs to move products from S&D centres to I&C centres, $\boldsymbol{PL1_{bij}}$. Table XIX numerically expresses the pollution-related costs to move products from I&C centres to sharing hubs, $\boldsymbol{PL2_{bjk}}$. Table XX numerically expresses the pollution-related costs to move products from I&C centres to reprocessing centres, $\boldsymbol{PL3_{bjl}}$. Table XXI numerically expresses the pollution-related costs to move products from sharing hubs to reprocessing centres, $\boldsymbol{PL4_{bkl}}$. Table XXII numerically expresses the pollution-related costs to move parts from reprocessing centres to the manufacturer, $\boldsymbol{PL5_{al}}$. Table XXIII numerically expresses the pollution-related costs to move parts from reprocessing centres to recycling centres, $\boldsymbol{PL6_{alm}}$.

Product, *b*	S&D centres, *i* \ I&C centres, *j*	*1*	*2*	*3*
1	*1*	0.059	0.048	0.048
	2	0.061	0.059	0.050
2	*1*	0.059	0.048	0.048
	2	0.061	0.059	0.050
3	*1*	0.059	0.048	0.048
	2	0.061	0.059	0.050
4	*1*	0.059	0.048	0.048
	2	0.061	0.059	0.050
5	*1*	0.059	0.048	0.048
	2	0.061	0.059	0.050

Table XII. Transportation-related parameter, TL1bij

Product, *b*	I&C centres, *j* \ Sharing hubs, *k*	*1*	*2*
1	*1*	0.057	0.048
	2	0.038	0.050
	3	0.050	0.044
2	*1*	0.057	0.048
	2	0.038	0.050
	3	0.050	0.044
3	*1*	0.057	0.048
	2	0.038	0.050
	3	0.050	0.044
4	*1*	0.057	0.048
	2	0.038	0.050
	3	0.050	0.044
5	*1*	0.057	0.048
	2	0.038	0.050
	3	0.050	0.044

Table XIII. Transportation-related parameter, TL2bjk

Table XIV. Transportation-related parameter, $TL3_{bjl}$

Product, b	I&C centres, j \ Reprocessingcentres, l	1	2	3	4
1	1	0.063	0.040	0.064	0.055
	2	0.057	0.050	0.044	0.042
	3	0.048	0.051	0.053	0.051
2	1	0.063	0.040	0.064	0.055
	2	0.057	0.050	0.044	0.042
	3	0.048	0.051	0.053	0.051
3	1	0.063	0.040	0.064	0.055
	2	0.057	0.050	0.044	0.042
	3	0.048	0.051	0.053	0.051
4	1	0.063	0.040	0.064	0.055
	2	0.057	0.050	0.044	0.042
	3	0.048	0.051	0.053	0.051
5	1	0.063	0.040	0.064	0.055
	2	0.057	0.050	0.044	0.042
	3	0.048	0.051	0.053	0.051

Table XV. Transportation-related parameter, $TL4_{bkl}$

Product, b	Sharing hubs, k \ Reprocessing centres, l	1	2	3	4
1	1	0.055	0.055	0.038	0.040
	2	0.051	0.057	0.059	0.059
2	1	0.055	0.055	0.038	0.040
	2	0.051	0.057	0.059	0.059
3	1	0.055	0.055	0.038	0.040
	2	0.051	0.057	0.059	0.059
4	1	0.055	0.055	0.038	0.040
	2	0.051	0.057	0.059	0.059
5	1	0.055	0.055	0.038	0.040
	2	0.051	0.057	0.059	0.059

Table XVI. Transportation-related parameter, $TL5_{al}$

Part, a \ Reprocessing centres, l	1	2	3	4
1	0.00014	0.00017	0.00014	0.00015
2	0.00014	0.00017	0.00014	0.00015
3	0.00014	0.00017	0.00014	0.00015
4	0.00014	0.00017	0.00014	0.00015
5	0.00014	0.00017	0.00014	0.00015

Table XXIV Numerically expresses the various parameters that are related to I&C centres. Table XXV numerically expresses the various parameters that are related to sharing hubs. Table XXVI numerically expresses the various parameters that are related to reprocessing centres. Table XXVII numerically expresses the various parameters that are related to recycling centres

Part, *a*	Reprocessingcentres, *l* \ Recycling centres, *m*	*1*	*2*
1	*1*	0.00015	0.00019
	2	0.00014	0.00014
	3	0.00016	0.00015
	4	0.00015	0.00013
2	*1*	0.00015	0.00019
	2	0.00014	0.00014
	3	0.00016	0.00015
	4	0.00015	0.00013
3	*1*	0.00015	0.00019
	2	0.00014	0.00014
	3	0.00016	0.00015
	4	0.00015	0.00013
4	*1*	0.00015	0.00019
	2	0.00014	0.00014
	3	0.00016	0.00015
	4	0.00015	0.00013
5	*1*	0.00015	0.00019
	2	0.00014	0.00014
	3	0.00016	0.00015
	4	0.00015	0.00013

Table XVII. Transportation-related parameter, $TL6_{alm}$

Product, *b*	S&D centres, *i* \ I&C centres, *j*	*1*	*2*	*3*
1	*1*	0.035	0.020	0.020
	2	0.038	0.035	0.023
2	*1*	0.035	0.020	0.020
	2	0.038	0.035	0.023
3	*1*	0.035	0.020	0.020
	2	0.038	0.035	0.023
4	*1*	0.035	0.020	0.020
	2	0.038	0.035	0.023
5	*1*	0.035	0.020	0.020
	2	0.038	0.035	0.023

Table XVIII. Pollution-related parameter, $PL1_{bij}$

Simulation. The proposed framework was modelled on GAMS Studio 26.1.0 in accordance with the MOMILP model. The relevant data was then integrated into the mathematical model, after which the simulation was conducted. The indices are referred to as sets, the decision variables as variables and the parameters as parameters and tables. The functions are referred to as equations. The case organization-data has been omitted in this study to avoid redundancy. Seeing as the MOMILP model has been initialized with the relevant data, the objective and the constraint functions are modelled in GAMS.

Results and discussion

The primary results of the simulation and optimization obtained based on the objectives functions and decision variables are disclosed in this section. It also discusses the sensitivity analysis carried out under various demand-based scenarios.

Product, b	I&C centres, j \ Sharing hubs, k	1	2
1	1	0.033	0.020
	2	0.008	0.023
	3	0.023	0.016
2	1	0.033	0.020
	2	0.008	0.023
	3	0.023	0.016
3	1	0.033	0.020
	2	0.008	0.023
	3	0.023	0.016
4	1	0.033	0.020
	2	0.008	0.023
	3	0.023	0.016
5	1	0.033	0.020
	2	0.008	0.023
	3	0.023	0.016

Table XIX. Pollution-related parameter, $PL2_{bjk}$

Product, b	I&C centres, j \ Reprocessing centres, l	1	2	3	4
1	1	0.040	0.010	0.043	0.030
	2	0.033	0.023	0.016	0.013
	3	0.020	0.026	0.028	0.026
2	1	0.040	0.010	0.043	0.030
	2	0.033	0.023	0.016	0.013
	3	0.020	0.026	0.028	0.026
3	1	0.040	0.010	0.043	0.030
	2	0.033	0.023	0.016	0.013
	3	0.020	0.026	0.028	0.026
4	1	0.040	0.010	0.043	0.030
	2	0.033	0.023	0.016	0.013
	3	0.020	0.026	0.028	0.026
5	1	0.040	0.010	0.043	0.030
	2	0.033	0.023	0.016	0.013
	3	0.020	0.026	0.028	0.026

Table XX. Pollution-related parameter, $PL3_{bjl}$

Model optimization. The MOMILP model was solved after integrating the initialization and the equations into the program. The weights W_1 and W_2 were assigned values from 0 to 1 in steps of 0.5 to produce a pay-off matrix that the decision-makers could view to choose an optimal compromise solution amongst the set of non-dominated solutions, in accordance with their priorities, scale, expectations and vision.

This mathematical model was solved using the CPLEX 12.8 solver in GAMS Studio 26.1.0 on a 64-bit Dell Inspiron 7559 PC with 2.60 gigahertz (GHz) Intel Core i7-6700HQ processing power and 8 gigabytes (GB) random access memory (RAM) in 3.960 s. Meanwhile, the same mathematical model was solved using the XPRESS 33.01 solver in 3.043 s. The original mathematic model contained 82 rows, 157 structural columns and 1,147 non-zero elements and the pre-solved mathematical model reduced the same to 40 rows, 45

Product, b	Sharing hubs, k \ Reprocessing centres, l	1	2	3	4
1	1	0.030	0.030	0.008	0.010
	2	0.026	0.033	0.035	0.035
2	1	0.030	0.030	0.008	0.010
	2	0.026	0.033	0.035	0.035
3	1	0.030	0.030	0.008	0.010
	2	0.026	0.033	0.035	0.035
4	1	0.030	0.030	0.008	0.010
	2	0.026	0.033	0.035	0.035
5	1	0.030	0.030	0.008	0.010
	2	0.026	0.033	0.035	0.035

Table XXI. Pollution-related parameter, $PL4_{bkl}$

Part, a \ Reprocessing centres, l	1	2	3	4
1	0.00007	0.00011	0.00007	0.00008
2	0.00007	0.00011	0.00007	0.00008
3	0.00007	0.00011	0.00007	0.00008
4	0.00007	0.00011	0.00007	0.00008
5	0.00007	0.00011	0.00007	0.00008

Table XXII. Pollution-related parameter, $PL5_{al}$

structural columns and 260 non-zero elements. The solutions obtained have been cross-checked with multiple mixed-integer solvers for verification purposes and the results were valid. Moreover, this mathematical model is robust in nature as it allows for the simulation of various decision-making routes by altering the number of suppliers, I&C centres, sharing hubs, reprocessing centres and recycling centres, as well as parameters related to economic and environmental costs associated with logistical operations.

Objective functions. This study generated a pay-off matrix that consisted of various decision-making scenarios to provide decision support to the case organization in the form of a tangible trade-off between the two objective functions and is numerically denoted in Table XXVIII.

Figure 5 numerically visualizes the objective-functions related to the pay-off matrix. Using this decision-support, the case organization chose to give a 65 per cent-weightage for economic utility and a 35 per cent-weightage for environmental impact, after careful consideration of its internal expectations, responsibilities and scalability of its operations.

Decision variables. After finalizing the weightages of the objective functions, the following data was sent to the case organization to integrate the same within its SCP operations. While multiple fields are expressed in the form of integers, the case organization was informed to round to the nearest whole number to render the data practical.

Table XXIX numerically expresses the decision variable regarding the number of products to be produced. Table XXX numerically expresses the decision variable regarding the number of products to be collected at I&C centres from S&D centres. Table XXXI numerically expresses the decision variable regarding the number of products to be sent to sharing hubs. Table XXXII numerically expresses the decision variable regarding the number of products to be sent to reprocessing centres. Table XXXIII numerically expresses

Part, a	Reprocessing centres, l \ Recycling centres, m	1	2
1	1	0.00008	0.00014
	2	0.00007	0.00007
	3	0.00010	0.00008
	4	0.00008	0.00006
2	1	0.00008	0.00014
	2	0.00007	0.00007
	3	0.00010	0.00008
	4	0.00008	0.00006
3	1	0.00008	0.00014
	2	0.00007	0.00007
	3	0.00010	0.00008
	4	0.00008	0.00006
4	1	0.00008	0.00014
	2	0.00007	0.00007
	3	0.00010	0.00008
	4	0.00008	0.00006
5	1	0.00008	0.00014
	2	0.00007	0.00007
	3	0.00010	0.00008
	4	0.00008	0.00006

Table XXIII.
Pollution-related parameter, $PL6_{alm}$

I&C centre, j	Product, b \ Parameters	$PC1_{bj}$	$EC1_{bj}$	$FC1_{bj}$	$Cap1_{bj}$
1	1	0.70	49.50	6.85	500
	2	0.95	52.25	7.50	460
	3	0.80	51.50	7.25	325
	4	0.65	48.75	6.75	440
	5	0.75	50.25	7.05	550
2	1	0.75	49.75	6.95	500
	2	0.90	52.00	7.45	450
	3	0.85	51.75	7.35	325
	4	0.60	48.50	6.85	425
	5	0.75	50.50	7.15	550
3	1	0.65	49.50	6.80	525
	2	0.85	52.50	7.55	450
	3	0.75	51.25	7.30	310
	4	0.65	48.75	6.70	435
	5	0.70	50.50	7.05	550

Table XXIV.
I&C centre-related parameters

the decision variable regarding the number of parts to be obtained from disassembly at reprocessing centres. Table XXXIV numerically expresses the decision variable regarding the number of parts to be refurbished at reprocessing centres. Table XXXV numerically expresses the decision variable regarding the number of parts to be recycled at recycling centres. Table XXXVI numerically expresses the decision variable regarding the number of parts to be sourced from suppliers

Sharing hub, k	Product, b	$PC2_{bk}$	$EC2_{bk}$	$FC2_{bk}$	$Cap2_{bk}$	$R3_{bk}$
1	*1*	3.15	88.25	15.75	325	73.00
	2	4.50	92.25	18.15	315	84.50
	3	3.50	91.50	17.25	220	80.30
	4	2.75	87.50	16.25	250	71.50
	5	3.25	90.15	16.75	315	75.50
2	*1*	3.05	88.50	15.65	320	70.70
	2	4.45	92.25	18.25	310	83.00
	3	3.45	91.75	17.20	225	82.90
	4	2.80	87.75	16.50	265	69.20
	5	3.20	90.30	16.80	320	77.00

Table XXV.
Sharing hub-related parameters

Re-processing centre, l	Part, a	$PC3_{al}$	$PC4_{al}$	$EC3_{al}$	$FC3_{al}$	$Cap3_{al}$	$R1_{al}$
1	*1*	1.07	10.40	265.50	32.75	1720	19.25
	2	0.75	7.30	260.25	31.50	1875	13.50
	3	0.46	4.45	156.75	18.75	1100	8.25
	4	0.26	2.55	130.25	17.25	1600	4.75
	5	0.18	1.75	110.15	16.25	1750	3.20
2	*1*	1.07	10.45	265.25	33.25	1700	19.30
	2	0.75	7.35	261.25	31.25	1950	13.65
	3	0.46	4.50	156.50	18.50	1125	8.40
	4	0.27	2.60	132.50	17.50	1550	4.80
	5	0.17	1.70	110.30	16.50	1750	3.15
3	*1*	1.07	10.40	265.50	33.25	1700	19.20
	2	0.74	7.25	261.25	31.50	1815	13.40
	3	0.46	4.50	156.75	18.50	1160	8.35
	4	0.26	2.55	132.50	17.25	1500	4.70
	5	0.17	1.70	110.50	16.65	1785	3.10
4	*1*	1.07	10.40	265.75	32.50	1625	19.25
	2	0.74	7.20	262.25	31.75	1850	13.35
	3	0.47	4.55	155.50	18.25	1200	8.40
	4	0.26	2.55	133.25	17.75	1550	4.75
	5	0.17	1.65	110.75	16.15	1850	3.05

Table XXVI.
Reprocessing centre-related parameters

Sensitivity analysis. The mathematical model was put through rigorous sensitivity analysis to determine the robustness of the framework in times of uncertainties in demand forecasting and routine shifts in the volume of demand. The mathematical model was evaluated under the scenarios ranging from a 15 per cent decrease in demand to a 15 per cent increase in demand.

Table XXXVII numerically expresses the volume of demand under the aforementioned scenarios. Table XXXVIII numerically expresses the results of the sensitivity analysis. Figure 6 visualizes the change in economic utility under sensitivity analysis. Figure 7 visualizes the change in environmental impact under sensitivity analysis

The results obtained from the sensitivity analysis of the mathematical model reinforces the robustness and flexibility of the framework under various demand-based scenarios.

Recycling centre, m	Part, a	$R2_{am}$
1	*1*	0.80
	2	0.85
	3	0.90
	4	0.70
	5	0.65
2	*1*	0.80
	2	0.80
	3	0.90
	4	0.70
	5	0.70

Table XXVII. Recycling centre-related parameters

Objective functions weights	Z_1	Z_2	Z_{eff}
$W_1 = 1.00$; $W_2 = 0.00$	52,506.6010	192.4370	~0.0000
$W_1 = 0.95$; $W_2 = 0.05$	52,506.6010	192.4370	−0.0160
$W_1 = 0.90$; $W_2 = 0.10$	52,506.6010	192.4370	−0.0320
$W_1 = 0.85$; $W_2 = 0.15$	52,179.9010	182.3170	−0.0480
$W_1 = 0.80$; $W_2 = 0.20$	52,179.9010	182.3170	−0.0660
$W_1 = 0.75$; $W_2 = 0.25$	52,140.2020	181.6100	−0.0850
$W_1 = 0.70$; $W_2 = 0.30$	52,140.2020	181.6100	−0.1030
$W_1 = 0.65$; $W_2 = 0.35$	52,140.2020	181.6100	−0.1210
$W_1 = 0.60$; $W_2 = 0.40$	51,609.6230	177.3070	−0.1400
$W_1 = 0.55$; $W_2 = 0.45$	51,609.6230	177.3070	−0.1590
$W_1 = 0.50$; $W_2 = 0.50$	49,635.9250	166.5450	−0.1790
$W_1 = 0.45$; $W_2 = 0.55$	44,499.7700	139.8600	−0.2100
$W_1 = 0.40$; $W_2 = 0.60$	44,499.7700	139.8600	−0.2430
$W_1 = 0.35$; $W_2 = 0.65$	44,499.7700	139.8600	−0.2760
$W_1 = 0.30$; $W_2 = 0.70$	39,344.8280	126.4540	−0.3130
$W_1 = 0.25$; $W_2 = 0.75$	25,239.1110	100.6650	−0.3540
$W_1 = 0.20$; $W_2 = 0.80$	−39,852.3000	0.0000	−0.4480
$W_1 = 0.15$; $W_2 = 0.85$	−39,852.3000	0.0000	−0.5860
$W_1 = 0.10$; $W_2 = 0.90$	−39,852.3000	0.0000	−0.7240
$W_1 = 0.05$; $W_2 = 0.95$	−39,852.3000	0.0000	−0.8620
$W_1 = 0.00$; $W_2 = 1.00$	−31,552,270.0000	0.0000	−1.0000

Table XXVIII. The pay-off matrix

These results also support our hypothesis that the economic utility and the environmental impact exhibit a positive correlation with changes in demand. Finally, these results also indicate that the capacity of the facilities in the integrated FL and RL network is sufficient to handle notable changes in demand.

Industry 4.0 mapping

While the mathematical robustness and the infrastructural flexibility of the proposed framework can be verified in an analytical matter, it is important to acknowledge the

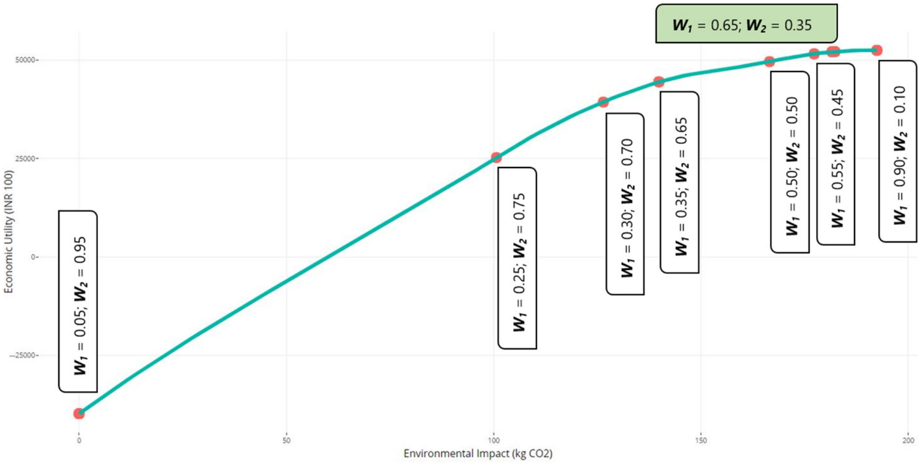

Figure 5.
Visualization of the pay-off matrix

Product, *b*	X_b
1	1,300.00
2	1,100.00
3	500.00
4	900.00
5	1,000.00

Table XXIX.
Decision variable, X_b

Product, *b*	S&Dcentres, *i* \ I&Ccentres, *j*	*1*	*2*	*3*
1	*1*	–	–	715.0000
	2	–	–	–
2	*1*	–	–	26.7857
	2	–	–	–
3	*1*	–	–	38.3929
	2	–	–	–
4	*1*	–	268.9286	–
	2	–	–	–
5	*1*	–	–	550.0000
	2	–	–	–

Table XXX.
Decision variable, Y_{bij}

implementation gap that exists in the industry. With the advent of radical and ground-breaking innovations in I4.0, it is imperative that society leverages these tools and technologies and map potential use-cases that can bridge this gap. A few of them are as follows:

- *IoT*: Data can be accumulated through cloud-powered sensors that are deployed on supply-chain related ecosystems such as production lines, inventory management systems, logistics systems and end-user devices. This data can then be transmitted on a real-time basis to facilitate quick decision-making scenarios.

- *Data Science*: Vast amounts of data accumulated through IoT systems can be segregated, cleaned and processed using sophisticated data science algorithms. This data can then be used for descriptive analytics to discover trends, outliers and key-drivers.

Product, b \ Sharing hubs, k	1	2
1	286.0000	–
2	10.7143	–
3	15.3571	–
4	107.5714	–
5	220.0000	–

Table XXXI. Decision variable, Z_{bk}

Product, b \ Reprocessing centres, l	1	2	3	4
1	–	429.0000	–	–
2	–	16.0714	–	–
3	–	23.0357	–	–
4	–	161.3571	–	–
5	–	330.0000	–	–

Table XXXII. Decision variable, W_{bl}

Part, a \ Reprocessing centres, l	1	2	3	4
1	–	–	–	2,175.8929
2	–	–	–	2,675.0000
3	–	–	1,637.5000	–
4	–	–	–	2,214.2857
5	–	–	–	1,691.0714

Table XXXIII. Decision variable, P_{al}

Part, a \ Reprocessing centres, l	1	2	3	4
1	1,196.7411	–	–	–
2	–	1,203.7500	–	–
3	–	655.0000	–	–
4	1,217.8571	–	–	–
5	845.5357	–	–	–

Table XXXIV. Decision variable, Q_{al}

- *Machine Learning*: Predictive algorithms can be utilized towards balancing demand-supply cycles and optimizing SCP operations to improve the agility of the logistical system. This can also be expanded to predict and optimize the parameters that affect the performance of an integrated FL and RL network.
- *Blockchain*: Distributed ledgers can be used to track the product lifecycle to enable a closed-loop regenerative system coupled with maintaining an accurate log of chronological information related to the product. This information can be leveraged

m Part, *a* \ Recycling centres,	*1*	*2*
1	979.1518	–
2	1,471.2500	–
3	982.5000	–
4	996.4286	–
5	–	845.5357

Table XXXV. Decision variable, Ram

Part, *a* \ Supplier, *c*	*1*	*2*	*3*	*4*	*5*
1	5,703.2589	–	–	–	–
2	–	8,496.2500	–	–	–
3	–	–	4,645.0000	–	–
4	–	–	–	6,182.1429	–
5	–	–	–	–	6,654.4643

Table XXXVI. Decision variable, Sac

Product, *b* \ Scenario	*+15%*	*+10%*	*Base Demand*	*−10%*	*−15%*
1	1,495.00	1,430.00	1,300.00	1,170.00	1,105.00
2	1,265.00	1,210.00	1,100.00	990.00	935.00
3	575.00	550.00	500.00	450.00	425.00
4	1,035.00	990.00	900.00	810.00	765.00
5	1,150.00	1,100.00	1,000.00	900.00	850.00

Table XXXVII. Volume demanded under different scenarios

functions \ Scenario objective	*+15%*	*+10%*	*Base demand*	*−10%*	*−15%*
Z_1	54,898.5240	53,979.0830	52,140.2020	49,689.4990	48,020.1780
Z_2	185.0420	185.0420	181.6100	175.4520	172.3730
Z_{eff}	−0.1250	−0.1230	−0.1210	−0.1220	−0.1230

Table XXXVIII. Results of the sensitivity analysis

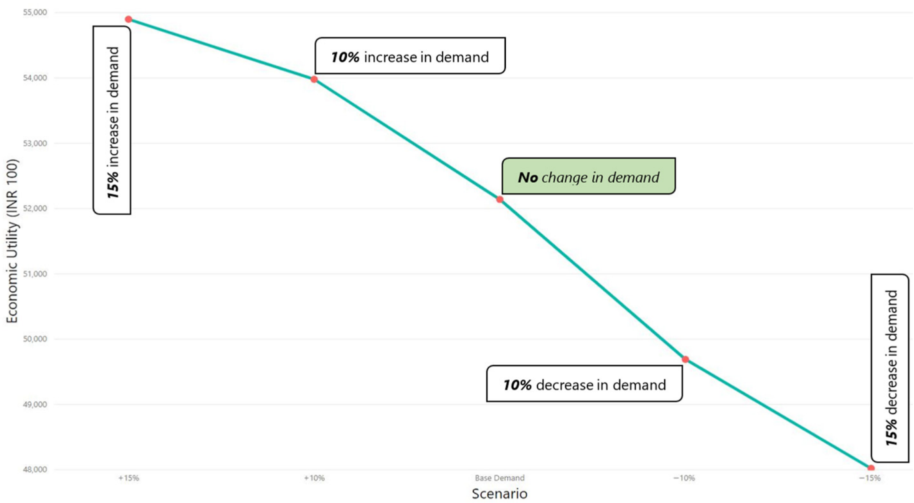

Figure 6.
Change in economic utility

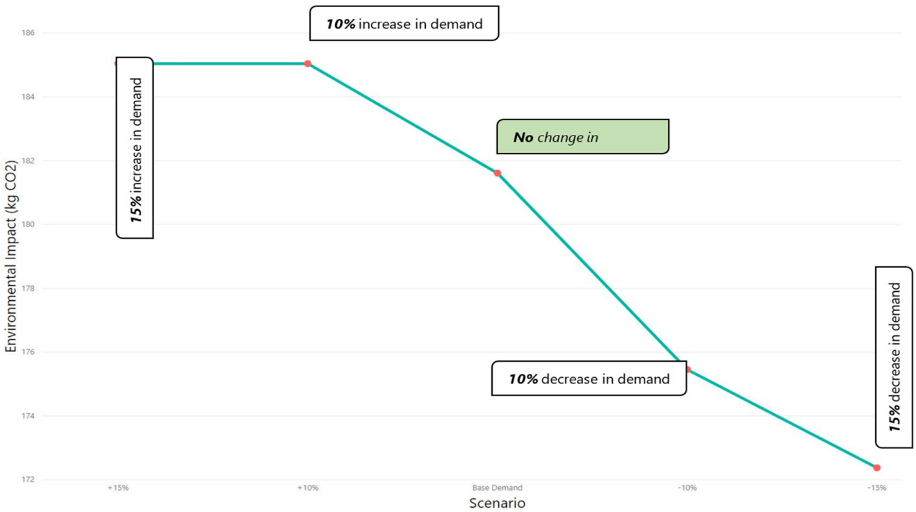

Figure 7.
Change in environmental impact

to track contractual usage in the customer network to facilitate end-of-lifecycle returns.

- *Genetic Algorithms*: Algorithms such as the non-dominated genetic algorithms, artificial Bee colony Algorithm and particle swarm optimization to optimize DSS operations by reducing the burden on computational resources.

Figure 8 visualizes an I4.0 framework to successfully transition from a linear economy to a CE through the linkage of SE networks.

Conclusion

It is quite understandable that there is a multitude of uncertainties that are related to the effective transition from a linear economy to a CE and/or SE, especially when constraints and variables that are related to environmental and economic factors are taken under consideration. The research reported started by analyzing relevant literature in this field, condensing key learnings from tried-and-tested frameworks used in the past. This study then continued to delve deeper by conceptualizing a novel integrated economy that links sharing networks to a circular production system. It does so with the aid of a robust and reliable MOMILP model that provides adequate decision support to key executives by quantifying the inherent trade-offs and limitations between multiple objectives for choosing an optimal compromise configuration within the generated set of non-dominated solutions.

The objective of the same was to optimize the economic and environmental objective functions of a case-company that wanted to incorporate a "zero-waste" philosophy into its operations. The costs and revenues associated with the production, distribution, collection, inspection, sharing, reprocessing, recycling and transportation were among the parameters that were collected from the case organization and injected into the model. The study proved that for the current configuration of facilities and the parameters attached, a weight-distribution of 65 per cent to the objective function concerning economic utility and 35 per cent to the one concerning environmental impact. This model was then put through rigorous sensitivity analysis to take into consideration various uncertainties in demand for production and distribution. This model is not only versatile but also is flexible with respect to incorporation in any closed-loop production system. This model then provided a quantifiable incentive to integrate principles and practices associated with a CE and/or SE. The study then outlined various use-cases of tools and technologies that are associated with I4.0 to enable and sustain transitions to this integrated economy.

Implications of the study

This holistic research study generated inferences that had a far-reaching influence over the way players involved in this study from the case organization. The theoretical, practical, managerial, social and environmental implications associated with the proposed work are discussed in the following subsections.

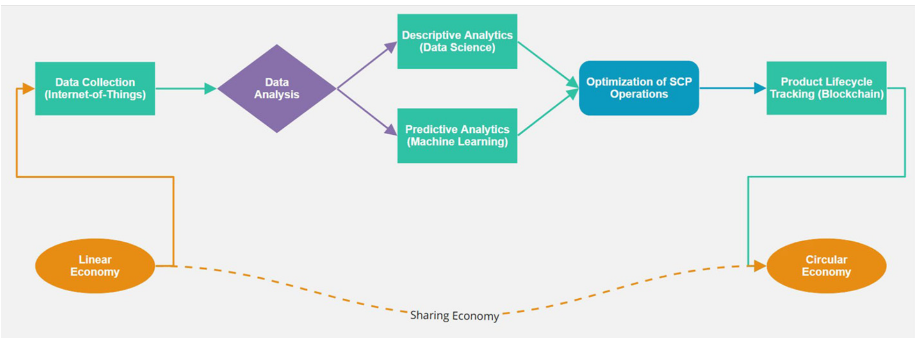

Figure 8.
I4.0 framework

Theoretical implications

The concepts explored in this research study analyze multiple approaches to aid linear supply chain transitions to a CE and/or SE, and by doing so, greatly contributes to the literature by bridging the knowledge gap that is prevalent in the manufacturing sector. The framework explored in this study incentivizes manufacturers not only to adopt a closed-loop approach but also to streamline the transition by incorporating aspects of a SE. The mathematical model explored in this paper provides a great deal of decision-support to key executives to effectively quantifying the intrinsic conflict between the economic and environmental factors associated with supply chain operations.

The insights presented in this study reaffirm our initial hypothesis that the two primary objective functions – economic utility and environmental impact exhibit a direct positive correlation. Hence, it is important to understand that the desired case, the maximization of economic utility and the minimization of environmental impact, cannot be reached at a mathematically ideal point. Thereby, this study explores the possibility of selecting an appropriate compromise solution through the non-dominated approach. As this study follows a MOMILP model, this study does not limit our framework to distinct factors alone. This not only provides a great deal of robustness to the framework but also allows for a great deal of customisation and flexibility to the key executives.

Practical implications

The lack of widespread awareness of economic utilities associated with incorporating CE and/or SE principles and practices hampers its integration in the Indian business paradigm. This is further weakened as most manufacturers view these practices with a great deal of scepticism and consider them as additional hindrances to their routine operations. The proposed framework for an integrated CE and SE coupled with a mathematical model provides a great deal of motivation and quantifiable incentives for contemporary manufacturing businesses to consider this mode of a supply chain transition. The MOMILP model further reinforces this approach by quantifiably proving the robustness and the reliability of this framework through numerical validation and sensitivity analysis.

The decision-support provided by this model greatly enhances the value-addition of this study by effectively bridging the knowledge gap between the realms of academia and business. The practical benefits are further compounded by the ability to drill-down on multiple factors that affect the SCP operations such as increasing/decreasing the size of the FL and/or RL networks, adjusting the capacities of the facilities and tweaking the costs and revenues associated with multiple operations on a per-product and/or per-part level. Furthermore, the ability to use tools and technologies associated with I4.0 greatly enhance the transition.

Managerial implications

The managers found it easy to adopt and adapt to this mathematical model developed, which helps them to reap success as they were able to visualize the benefits using the pay of matrix, just by using the data available within the company. The managers found the model beneficial as they were able to be both cost-effective and also environmentally positive. The stakeholders also understood the scope of sharing networks in the circular economy and agreed on the need for transition from a linear economy to CE with the digital tools and techniques of I4.0.

Social implications

The integration of CE and/or SE principles and practices in a manufacturing environment greatly enhances the collaborative use of assets and services alike. Even though supply chain frameworks and mathematical models can quantify and incentive factors relevant to this transition, it is imperative to understand that the people involved form the key backbone of the entire process. The participants of this integrated economy are communities, individuals, organizations, associations and business, all of whom are heavily embedded in an extremely efficient economy, one made by and for the people.

Within business environments, human rights and individuality are highly valued, with their ideas and opinions integrated into the operational model at all levels. Another key takeaway from this study is the influx of job opportunities created by the effective implementation of this framework. In this manner, business is accessible and open to anybody who wishes to operate on any echelon of this framework. Internet networks and technologies further enable the research and development of products, services and business models in a collaborative manner, one that transcends geographical boundaries. It is also important to understand that when businesses can satisfy the demand of a community with lesser supply, they can do so at an extremely efficient level, both with respect to pricing and quality standards.

Environmental implications

In an integrated economy that incorporates practices and principles that are associated with a CE and/or SE, waste is effectively eliminated as it's fundamentally viewed as an under-used and/or un-used resource that can be linked back into the system. This approach places the planet at the core of the economy as production, value-addition and distribution operate in a harmonic paradigm while limiting the economic impact of those activities. In that regard, products and services are designed with sustainability in mind as opposed to obsolescence. This, in turn, promotes not only the perpetual re-use of valuable resources but also gives rise to business models that deliver a positive impact on the planet. The results that stem from this research study indicate that environmental impact can be optimized without drastic losses to the economic utility by effectively using the power of sharing networks.

Limitations and future scope

There is tremendous scope for future work in this arena as this study only considered a basic FL and RL network with less than five facilities of each kind. Also, future work can be focussed on integrating social objective functions that consider jobs created, the standard of living and democratic indicators among other factors. Furthermore, future work can expand the current framework to include multi-period models in the place of the single period model that was analyzed in this study.

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