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Environment and economic analysis of reverse supply chain scenarios for remanufacturing using discrete-event simulation approach

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Abstract

The study covers the concepts involved in reverse supply chain modeling using the case of a manufacturing company. The purpose of this study is to build a sustainable reverse supply chain model for resource conservation through remanufacturing of stator shafts by using a discrete-event simulation approach. The simulation studies in the reverse supply chain have taken up cases of either plastic or electronic waste remanufacturing, while very limited studies deal with simulation of sustainable reverse supply chains using a manufacturing industry case study from international customers. In this study, reverse supply chain using simulation study in manufacturing sector is carried out using Arena Rockwell simulation software. The simulation model is built using discrete-event simulation for returns from customers of two developed countries, i.e., Germany and the USA to Chennai, India. The study emphasizes full container load and less than container load modes of shipment scenarios and multiple return cases. The comparative analysis suggests that the value-added and non-value-added time of the reverse supply chain is slightly greater in the less container load scenario. The wait time per entity in remanufacturing processes similar for both shipment scenarios varies significantly based on return cases. The cost and carbon emission associated with transportation, in the reverse supply chain inclusive of social carbon cost, have also been estimated. Therefore, the study proposes a possible sustainable reverse supply chain framework that could be adopted by different manufacturing industries and yield opportunities for performance improvement.

Keywords Reverse supply chain · Remanufacturing · Environment · Economics · Supply chain modeling · Discrete-event simulation

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1 Introduction

A closed-loop supply chain is defined as the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with the dynamic recovery of value from different types and volumes of returns (Krikke et al., 2013). The relationship between a closed-loop supply chain and a reverse supply chain is closely linked (Kazemi, et al., 2019). The reverse supply chain is considered a subset of the closed-loop supply chain (Fu et al., 2021). In a closed-loop supply chain, the manufacturer obtains products from the consumer in exchange for value, recycles them for profit, ensures quality, and implements modifications for improving the quality (Giri et al., 2017; Taleizadeh et al., 2019), while reverse logistics refers to the collection of materials, resources, and parts that are to be recycled, repaired, refurbished, and remanufactured (Jalil, 2019). The reverse supply chain can also be defined as the process of dealing with the backward flows of used/damaged products (cores) or materials that include activities such as collection, inspection, reprocessing, disposal, and redistribution (Fazlollahtabar, 2018). The global reverse logistics market was valued at 415.2 US dollars (USD) in 2017 and by 2025, the reverse logistics market is expected to reach 603.9 billion USD (Musari & Zaroni, 2021). The output of remanufacturing is worth $75 billion and provides 180,000 full-time jobs in the USA (Cao et al., 2020). It is important to note that the service of an organization does not end once after delivering the product. Customer service is a unique key factor that decides the customer's loyalty to the organization (Vilkaite-Vaitone & Skackauskiene, 2020). Returns through the reverse supply chain for remanufacturing also lead to an increase in customer satisfaction (Mishra et al., 2021). Returns being unavoidable in most cases are generally considered as negative sales and impact the accountability of the organization (Xu et al., 2018). Therefore, efficient usage of reverse supply chain and logistics will cut down unnecessary costs and material usage, reducing the impact caused by returns and recalls on the financial performance of the organization (Vlachos, 2016). Most companies give significance to the forward supply chain for gains in cash flows while often ignoring the importance of the reverse supply chain. On the other hand, in view of the long run, consideration of the reverse supply chain is an essential factor to increase profit since the raw material cost can be reduced greatly (Garg et al., 2020). The reverse supply chain ensures recovered resources feed loops that facilitate better supply by converting old products into raw materials (Boronoos et al., 2021).

A sustainable reverse supply chain aims to consider environmental problems in the areas of the reverse supply chain by reducing the overall negative influence of the supply chain on the environment and taking into account the economical part that represents the cost of waste (Ali et al., 2018). Sustainability is becoming a key factor in development because of its role in tackling several environmental harms (Koval et al., 2021). For example, most European countries where air pollution is considered less than the rest of the world itself show high pollution that would bring dramatic consequences for society and the economy regarding people's health and extra costs for such issues (Torkayesh et al., 2022). Companies seeking sustainability goals gain lower health, labor, and disposal costs, better safety, reduced turnover and recruitment costs, diminishing absenteeism rates, shorter lead times, a high level of motivation, productivity, and increased brand image (Coşkun et al., 2022). Even sustainability inclusions are encouraged in manufacturing industries. The key criteria for selecting sustainable reverse supply chain performances can usually include cost, time, recycling efficiency, quality, and waste. Reverse supply chain implementation in manufacturing industries should be economically, environmentally, and socially applied. Application of a reverse supply chain in manufacturing results in effective economical practices through recycled outputs and reduction in losses. The sustainable reverse supply chain in a manufacturing organization can provide myriad benefits for the business's finances, customers, and the environment (Kumar & Bangwal, 2022). These include increased return on investment, reduction in losses and unplanned revenue, improved environmental sustainability, reuse encourages competition in manufacturing, satisfactory clients, and enhanced data protection (Pochampally et al., 2009; Shekarian, 2020). The reverse supply chain can be used to reduce, reuse, recycle, remanufacture, redesign and recover. One of the most prominent sustainable development goals prescribed by the United Nations, i.e., responsible consumption and production (Sustainable Development Goals-12) is achievable using a reverse supply chain. Sustainability parameters such as environmental performance, energy consumption performance, and social responsibility can also be increased (Ethirajan et al., 2021). A sustainable reverse supply chain serves useful particularly when there is a risk of supply of critical raw materials. Moreover, the remanufacturing of components consumes less energy compared to manufacturing a new component and leads to reduced carbon dioxide emissions (Zhang et al., 2020). Ultimately, it also helps in the reduction of products that are sent to landfills, thus reducing the effect of landfills on the environment (Yang et al., 2021). The concept of a reverse supply chain comprises several advantages emphasizing its importance. The significance of the reverse supply chain provides an opportunity to perform various research studies and address respective research questions.

Supply chain analysis is the act of assessing each step of a supply chain, beginning with the time the company purchases supplies or raw materials from its suppliers and terminating with the delivery of finished goods to the customers (Ülkü & Engau, 2021). The goal of the analysis is to identify which link in the supply chain may be reduced or enhanced to deliver the goods to customers more swiftly and effectively (Sürie & Wagner, 2005). Likewise, the goal of a reverse supply chain analysis is to identify which components of the supply chain can be enhanced in such a way that each return is efficiently handled. Although there exists literature on the analysis of supply chain there are few studies that addressed analytics of reverse supply chain considering sustainability, transportation, and remanufacturing bottlenecks.

Research questions addressed by the study are:

RQ1. How does a sustainable reverse supply chain work in the manufacturing industry?
RQ2. How to analyze the prominent factors of a supply chain using simulation?

The study will subsume the manufacturing industry into the array of existing sectors in reverse supply chain studies. Modeling of a reverse supply chain has been primarily concentrated on optimizing the number of distribution centers and disassembly facilities since they have only dealt with case studies of electronic supply chains. The case study having functioning international warehouses gave an advantage of optimizing the remanufacturing process which has been seldom addressed. Reverse supply chain modeling studies often focus on the cost of transportation but omit the inclusion of sustainability factors. Once the overall understanding of the research is adopted, it is essential to benchmark objectives essential for thoroughly executing the study.

Hence, the research objectives of this study are:

RO1. To model the working of the reverse supply chain in a manufacturing industry pertinent to the real-world application.

RO2. To analyze the prominent factors of a supply chain such as fill rate, transfer time, value-added and non-value-added time with emphasis on different modes of transport and multiple return cases.

The novelty of the study is to include returns from two international customers in reverse supply chain simulation. Previous studies of reverse supply chains rarely dealt with returns from a specific province and country and usually consider single-customer returns. The research contributes to the literature by developing a simulation model of the reverse supply chain using two customers considering two modes of shipment scenarios along with multiple return cases. The simulation model built explains and compares the effects of the mode of shipment and different types of returns on prominent factors of the reverse supply chain. It focuses on process analysis and optimization for a smooth workflow while previous studies focused on distribution, collection centers, policy, and regulation optimization. It also summarizes the range of carbon emissions and costs correlated with transportation in the reverse supply chain of both international customers. This study deals with reviving defective products that paves way for remanufacturing instead of manufacturing a product from scratch in which investments are misspent in acquiring new resources. This framework can also act as a reference for studies in electronic waste recycling and plastic recycling even flexible for multiple international customers and multiple returns cases research. Remanufacturing used products aid to cut down huge expenses made on renewing resources for future production. As a result, product and service prices might be reduced creating space for the advent of new clients and an increase in competition in the manufacturing industry. Furthermore, keeping in mind the environmental sustainability factors, the study focuses on addressing prominent merits of a sustainable reverse supply chain such as return on investment, reuse encouraging competition in manufacturing, and improved economic and environmental sustainability.

The subsequent sections of the paper present a literature review in relevance to reverse supply chain modeling using a simulation study and discuss past literature. In Sect. 3, problem formulation and methodology are explained. Section 4 provides a perspective of the overall case study. Thereafter, the simulation model created using Arena simulation is briefly explained in Sect. 5. The verification and validation of the model are described in Sect. 6. The results and discussion elucidated in Sect. 7 show the key results that are derived from the simulated model that serve useful for the manufacturing industry. It is followed by the conclusion in Sect. 8, which summarizes the research paper with limitations and scope for future research.

2 Theoretical background

Remanufacturing is defined as an industrial process that returns a product to its original conditions with a guarantee that it is equivalent to or better than the product manufactured initially, through inspection, disassembly, cleaning, reprocessing, assembly, and testing (Eguren et al., 2018). Remanufacturing plays a vital role in the closed-loop supply chain (Hong et al., 2020). There are several advantages that are related to remanufacturing. It is an environmentally friendly product recovery method and contributes significantly to carbon emissions reduction. Remanufacturing is an energy-efficient method in production and its application has grown immensely nowadays. It is considered important for a sustainable future. Industrial applications of remanufacturing include aircraft components, automotive components, electrical appliances, medical equipment, and furniture components.

The concept of the reverse supply chain was first studied in the 1990s, thereby gaining its importance in the 2000s (Saruchera & Asante-Darko, 2021). The reverse supply chain is defined as "*The process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal*" (Govindan et al., 2019). In general, a reverse supply chain designs a set of activities to recover end-of-life and after-use products and intermediate by-products by the original equipment manufacturers (OEMs), suppliers, or any third parties (Mokhtar et al., 2019). Pokharel and Mutha (2009) have analyzed perspectives in reverse logistics where works of literature before 2009 were reviewed and the following conclusions were drawn. It is found that the research using case studies on the topics of reverse supply chain was focused on all aspects but studies focusing on the mathematical modeling and simulation methods were limited. Chanintrakul et al., (2009) presented a comprehensive review of the literature on reverse logistics network design from the period 2000–2008. The literature was classified into six streams based on the model namely the impact of uncertainty, stochastic models, the transportation impact, analysis of multi-agent character, a hazardous waste reverse logistics network, and simulation models. It has been concluded that there has been a gradual increase in efforts in modeling reverse logistics networks but there is a need for incorporating more realistic and complicated assumptions. Agrawal et al., (2015) reviewed reverse supply chain literature due to the significance of reverse logistics. It is mentioned that reverse logistics is still in its evolving phase and issues pertaining to the adoption and implementation of reverse supply chain modeling, forecasting product returns, and reverse supply chain from a secondary market perspective, have not been addressed extensively.

There exists a range of literature on reverse supply chain modeling using several theoretical and mathematical methods (Jeihoonian et al., 2020; Kosacka-Olejnik & Werner-Lewandowska, 2020). For example, Pishvaee and Torabi (2010) have utilized a bi-objective mixed integer linear programming for closed-loop supply chain modeling problems. Gharye Mirzaei et al. (2022) propose a dual-channel network of a sustainable Closed-Loop Supply Chain (CLSC) for rice considering energy sources and consumption tax. A mixed integer linear programming model is formulated for optimizing several factors in the proposed supply chain network under uncertainty. Moreover, four multi-objective metaheuristic algorithms are employed to solve the model and the results indicate that up to 19% of electricity can be saved by constructing solar panel sites and producing energy out of rice waste. Goodarzian et al. (2022) developed a four-echelon, multi-objective model for the green-cold vaccine supply chain network during the COVID-19 pandemic. The study aimed at reducing supply chain costs, demand coverage, delivery time, and adverse environmental effects with the use of the Internet of Things. The results of the study show that 17 temporary vaccination centers and 14 temporary treatment centers have been established according to the appropriate factors.

The studies that have adopted simulation methods to address problems in reverse supply chain modeling are limited (Mathiyazhagan et al., 2020). Discrete-event simulation is a method used to model real-world systems and is the process of illustrating the behavior of a complex system as a series of well-defined and systematic events. In a situation involving complex and intricate details, it is better to use simulation methods to solve a model. The range of applications of simulation in models is wide. For example, Kamran et al. (2022) presented a stochastic simulation–optimization model that is developed for the COVID-19 vaccine supply chain network. A system dynamics-based simulation model was used to investigate the COVID-19 outbreak in universities. A new stochastic multi-objective, multi-period, and multi-commodity simulation–optimization model has been developed for the COVID-19 vaccine's production, distribution, location, allocation, and inventory control decisions. The results suggested that as the quarantine period decreases, the mortality rate increases with a slight slope. Then, by the quarantine period drop of 20%, the mortality rate increases by 10%. Arena is a discrete-event simulation software and discrete-event simulation is effective compared to other existing techniques. It is suggested by Lieder et al. (2017) that cost, CO_2, and material-saving effects over time can be quantified using agent-based product architectures and discrete-event supply chains. This significantly reduces uncertainty when it comes to evaluating the circular design and business approaches at the early design stage and leads to improved decision-making about circular system implementation. The review of the reverse supply chain pertaining to the study has been performed and is given in Table 1.

Arena simulation is used to develop a reverse logistics network for the collection of batteries from the customer that has attained its EoL (Jayant et al., 2014). Waste from electrical and electronic equipment refers to domestic appliances, IT and telecommunications equipment, monitoring, electrical, and electronic tools (excluding large-scale stationary industrial tools), control instruments, and similar items (Hosseini-Motlagh et al., 2022). The importance of transportation is also been highlighted by one of the most prominent studies on waste from electrical and electronic equipment by Kara et al., (2007) in which reverse logistics networks for collecting end-of-life appliances in the Sydney Metropolitan Area have been discussed. The incorporation of different transportation modes is not included, and its effect on the reverse supply chain is generally not highlighted in the literature. In the forward supply chain, there exist several attempts to include sustainability designing of the supply chain. Williams et al., (2020) have attempted to design a green supply chain using network partitioning where they conducted a sensitivity analysis to study the effect of a carbon tax in encouraging a greener system considering various scenarios under which emissions might increase or decrease. Specific scenarios lead to a lower overall GHG emission in the modeling of the green supply chain. Further, the implementation of the reverse supply chain itself is a sustainable step for a better society. Although there exist several kinds of research on sustainability in the reverse supply chain (Flygansvaer et al., 2018), sustainability assessing factors and incorporation of sustainability factors are not considered while modeling a new reverse supply chain, especially in simulation modeling. The social cost of carbon has been included in the study which is considered the most important single economic concept in climate change economics (Nordhaus, 2017). The social cost of carbon is an estimate of the economic damages that would result from emitting one additional ton of greenhouse gases into the atmosphere (Wang et al., 2019). There exists a moderate number of papers that deal with global-scale reverse supply chain modeling through mathematical methods. For example, Bing et al., (2015) have redesigned the global reverse supply chain for household plastic waste. A scenario study based on a mixed-integer programming model is used for the global network design for plastic waste recycling (Bing et al., 2015). The study was conducted using the case study of plastic waste generated from the Netherlands handled by a supply chain with relocated reprocessing facilities to China. The previous studies of reverse supply chain modeling are usually constrained to one particular province or within a specific country.

The studies that deal with modeling a sustainable reverse supply chain are typically focused on the location of disassembly, distribution, and collection centers since it has

Table 1 Review on reverse supply chain

S.No	Methodology	Description	Reference
1	ReSOLVE model of circular economy approaches	Remanufacturing model examines the trade-off between set-up delays and availability of green transportation	Dev et al., (2020)
2	Structural equation modeling	Investigates the role of SC leadership styles on suppliers' performance dimensions related to reverse product flows	Mokhtar et al., (2019)
3	Mixed integer linear programming (MILP)	A tire forward and RSC is designed to integrate customer relationships and SCM	Yadollahinia et al., (2018)
4	Stochastic matrix	Evaluate the support of WEEE management system Italian organization with specific focus on the collection centers	Isernia et al., (2019)
5	Mathematical modeling	Proposed configuration to minimize the total costs of RSC with respect to inspecting	Fazlollahtabar (2018)
6	System dynamics approach	Presents a model to represent complex RSC system to recover used products at their end-of-life stage using an electric vehicle battery case study	Alamerew and Brissaud, (2020)

dealt with plastic wastes, household equipment wastes, and waste from electrical and electronic equipment returns (Abid et al., 2021). Das and Dutta, (2012) developed a framework that has been studied for an integrated forward and reverse supply chain. The author discussed a simulation model based on system dynamics methodology to study the conduct of a multi-echelon forward-reverse supply chain has been used. Kumar and Yamaoka (2007) conducted a study focusing on the closed-loop supply chain of a Japanese automotive company using a system dynamic modeling approach. The results suggested that the growth of the used car export rate to emerging countries can be triggered by Japanese end-of-life vehicle regulation. Moreover, the reverse supply chain is uncertain unlike the forward supply chain (Fazli-Khalaf & Hamidieh, 2017; Ghasemi et al., 2022) as the demand in case of returns is vaguely uncertain and independent of time constraints. It is noticed that previous studies have not highlighted the effects of different types of return cases on the remanufacturing reverse supply chain.

Tako and Robinson et al., (2012) state that even though the discrete-event simulation approach is used more frequently than the system dynamics to solve logistics and supply chain management-related problems, the use of the discrete-event simulation approach or system dynamics approach depends on the logistics and supply chain management issue. Shi et al., (2010) designed mixed integer linear programming and discrete-event dynamic simulation methods for television remanufacturing. Further, Golroudbary and Zahraee (2015) simulated a closed-loop supply chain case study by utilizing the concept of system dynamics to study the system behavior of an electrical manufacturing company that has been evaluated by simulating the closed-loop supply chain. The study was carried out to tackle the issues of customer satisfaction. Simonetto et al., (2018), studied a waste remanufacturing model that focuses on household equipment. The simulation model results reveal that instead of discarding the household equipment, remanufacturing is a viable alternative.

There exist several works of literature that deal with reverse supply chain, but it is mentioned by Mathiyazhagan et al., (2020) that only a small proportion of them deals with reverse supply chain modeling through mathematical programming and simulation techniques. Moreover, Abid et al., (2021) added that the number of literatures that deals with reverse supply chain modeling using simulation proved to be limited. Furthermore, simulation studies in reverse supply chain simulation were largely focused on plastic waste, household equipment, and waste from electrical and electronic equipment for example Kara et al., (2007) and Jayant et al (2014). But only limited studies exist on the simulation of a reverse supply chain using a case study from the manufacturing industry. Moreover, despite the significance of transportation in the reverse supply chain, different modes of transportation and their impact on the reverse supply chain are not reported. Also, the previous attempts deal with reverse supply chain simulation studies that are usually constrained to a single customer within a particular province and country. Additionally, the incorporation of sustainability measure factors is usually neglected while modeling a reverse supply chain through a simulation study. Hence, in this study sustainable reverse supply chain particularly focuses on the case of a manufacturing industry that deals with returns from two different customers from two different countries. Reverse supply chain modeling using simulation is carried out using Arena Rockwell simulation software with the incorporation of feasible real-world transportation modes, different types of return case scenarios, and sustainability factors.

3 Methodology

The literature gaps identified from the theoretical review on the sustainable reverse supply chain simulation studies and discussions held with industrial executives were used to identify the existing problem in the industry. Then, the identified problem has been defined. An appropriate work plan and framework have been formulated accordingly. An overall framework was built comprising the working of a reverse supply chain, entities involved, warehouses, and the flow of products. Data regarding the transfer time, process involved and the cycle time of processes were collected from the case organization. The study is based on discrete-event simulation since it is flexible and allows the model of the dynamic behavior of a real system. The arena is a discrete-event simulation software by Rockwell automation that allows the modeling of a continuous process. It provides an integrated framework for building simulation models in a wide variety of applications. Moreover, it is feasible to use Arena software on any computer meeting its minimum requirements. Consequently, a reverse supply chain model was built and simulated using discrete-event simulation-based Arena simulation software Version 14 on an Acer computer. The appropriate implications of the study were inferred from the simulation results. The methodology adopted in this study is shown in Fig. 1.

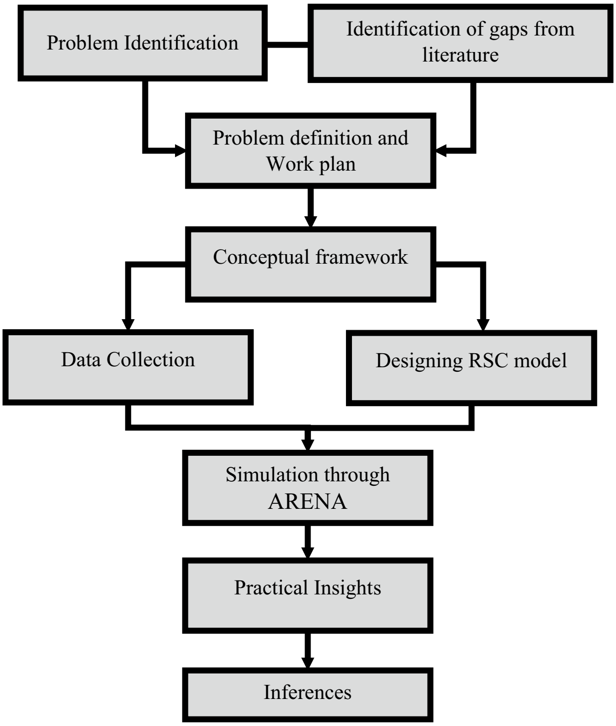


Fig. 1 Methodology adopted

4 Case study

The study deals with reverse supply chain modeling using the case of a manufacturing organization. Chennai is used for the study because of its geographical advantage, i.e., accessibility to seaports and the plethora of opportunities it provides for industrial research. Moreover, in terms of industrial output, Chennai is the largest contributor to the automobile sector in the country. The case company is situated on the outskirts of the city. In Chennai, the company has two major manufacturing units. One is dedicated to manufacturing radiator caps and gear shifters while the case company unit focuses on manufacturing powertrain components. The case organization manufactures a variety of high-quality fastening and shaft components and is situated in Chennai, Tamil Nadu, India. The stator shafts are used in passenger car transmissions. The processes of manufacturing a stator shaft include forging, normalizing, drilling, hobbing, boring, grinding, inspection, and washing. The manufactured components are shipped to several countries such as Germany and the USA. The component supplied to the customer by the supplier could have been faulty or damaged during shipping. The component supplied would not have met the requirements of the customers and could have been up to the standard requirements but a complementary component of the same part that has been manufactured by some other supplier could have not met the measurements. Therefore, a customer could ask the supplier to remanufacture the product lot according to the correct fit measurements.

The case organization is aiming to increase its supply to the customers and they want to be prepared in case there are returns from its future customers as per the numerous possibilities of returns. The stator shafts are bought in bulk by automotive companies from the USA and Germany. When the shafts are returned from the customers two modes of transport scenarios, i.e., full container load and less than container load are considered. The goods in a container if owned by a single party it is referred to as a full container load. If the goods in a container involve multiple shippers' goods together, it is referred to as less than the container load. Less than container load can be used for shipments as little as 1 cubic meter, or less, although the minimum. Any shipment can use the Full Container Load agreement, regardless of the volume. However, it is best to consider a full container if the total space that the load consists of is 15 cubic meters or more. The difference between the two scenarios is discussed in Table 11 included in Appendix 2. In full container load mode shipment, shafts are transported from the customer to the warehouse of the supplier located in the respective country and are directly sent to the for-loading cargo followed by customs for shipment. Once the cargo is received in Chennai port it again undergoes the customs procedure and is directly routed to the location of the supplier industry as shown in Fig. 2. Figure 3 shows the mode of transportation in less than container load. Thereafter, using inland transportation, the shafts are delivered to the supplier industry.

The company is motivated to adopt and implement a reverse supply chain since they lack a proper sustainable reverse supply chain network. It is also estimated that the remanufacturing of return in the customer's country prove to be extremely expensive than shipping the returns and remanufacturing in Chennai. Thus, overall economic sustainability can be established

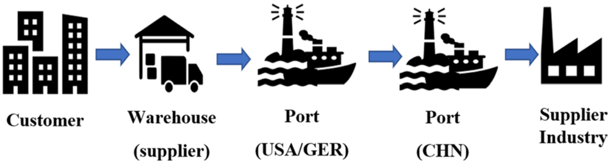


Fig. 2 Full container load mode of shipment

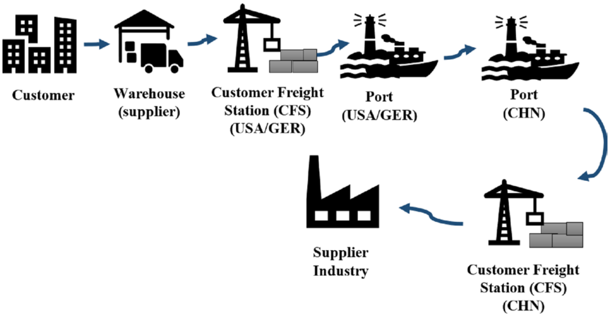


Fig. 3 Less than container load (LCL) mode of shipment

and customer savings can be enhanced by remanufacturing the returns in Chennai. The study would help in adopting a sustainable reverse supply chain and would act as a framework in case of real returns. The need for a reverse supply chain and its importance from an economic perspective is given in Table 2, and calculations are discussed in Appendix 1 where the USA and Chennai (CHN) were considered.

The economic benefit of the customer is given in Table 2 for remanufacturing the number of products that fit a 20 ft container. Customers have to spend only the shipping charges of 1600 USD as freight charges and around 65,000 USD will be saved by the customer if they decide on remanufacturing in India. The total cost for remanufacturing 18 pallets of shafts in India would be approximately 10,000 USD and the total cost if remanufactured by the customer would be approximately 67,000 USD. The overall saving is huge in terms of economical perspective approximately 57, 000 USD, and thus, the reverse supply chain simulation study is significant.

5 Model formulation

Figure 4 presents the sustainable reverse supply chain structure for a core transported from Germany to the supplier's location in India. The reverse supply chain of the stator shaft includes collection, documentation, transportation, remanufacturing, and inspection. The initial stage of the reverse supply chain in a manufacturing sector is the identification of faults in procured components from the supplier. Once the customer has decided that the components have to be returned, an advance shipment notice will be generated by the customer. An advanced shipping notice is a notification document that provides detailed delivery information. After the generation of the advanced shipping notice by the customer, the faulty components are routed to the respective warehouses of the supplier company. A similar reverse supply chain model was formulated using Arena simulation software. As shown in Fig. 12 in Appendix 3, the identified shafts in Germany are shipped to the supplier warehouse situated in Germany and similarly, the shafts are shipped to the warehouse in the USA after the generation of advanced shipping notice.

Once the component reaches the respective warehouse, the decision for opting for the suitable freight organization for the shipment of components from the warehouse to Chennai port is performed in deciding the freight forwarder module. When an ideal freight organization has been selected, the information related to the estimated cost for shipment and time of delivery is sent to the customer and supplier, respectively. After getting approval from both ends, the selected freight company is booked for shipping the

Table 2 Cost–benefit estimation

	Customer's cost (USD)	Overall cost (USD)
Total cost of Labor in USA	21,600	16,560
Total machine cost in USA	57,600	50,400
Total cost in USA (without shipping)	79,200	66,960
Shipping cost USA to CHN	1600	1600
Total cost in USA	–	68,560
Total cost of Labor in CHN	–	191.70
Total machine cost in CHN	–	1,916.99
Total cost in CHN (without shipping)	–	2,114.98
Shipping cost CHN to the USA	–	8000
Total cost in CHN	–	10,115
Savings	77,600	58,445
Conclusion	Profitable for the customer to ship for remanufacturing rather than remanufacturing in the USA	Profitable for both the customer and supplier (overall) to remanufacture in India rather than remanufacturing in the USA

components. After confirming the booking, the components are transported to the respective seaports for export. In Germany, three shipping organizations are usually considered for shipping products to Chennai Seaport namely GER_companyA, GER_companyB, and GER_companyC. After booking, if the mode of shipment is full container load, then the components from the supplier warehouse are routed to the nearest seaport in Germany as shown in Fig. 13a. If the mode of shipment is less than the container load, then the shafts are transported to the container freight station owned by the freight forwarder nearby the seaport as shown in Fig. 13b. Similarly, the case of US customer returns is depicted in c and d in Appendix 3.

In the full container load scenario, after the arrival of components in the port, the cargo is loaded inside the container, and the shipping organization creates a commercial invoice. Thereafter, a packing list will be created by the freight forwarder and a bill of loading is generated which is issued by the carrier to the shipper of goods. These documents are vital for exporters to get paid and importers to receive their goods. Finally, the cargo undergoes customs clearance by the respective country officials, and it is shipped to Chennai port as shown in Fig. 14a in Appendix 3. In the less-than-container load scenario, the parts are transported from the supplier warehouse to the container freight station as shown in Fig. 14b Appendix 3. The custom processes for less than container load are the same as full container load as shown in Fig. 14c Appendix 3. The procedure completion could be a little delayed in the less-than-container load scenario since there will be multiple documentation for goods from multiple clients of the freight forwarder in a container.

Once the components reach Chennai port, it is again subjected to customs clearance by Indian government officials. As shown in Fig. 15a Appendix 3, after clearance, those

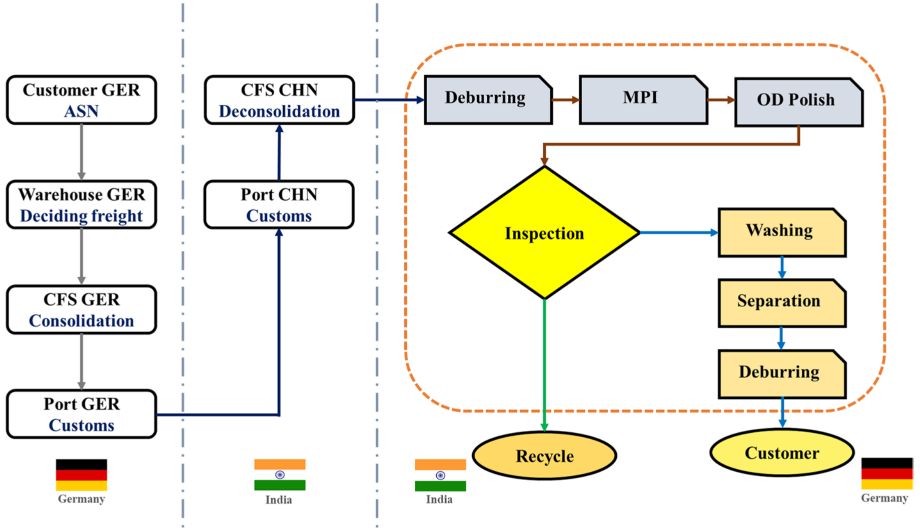


Fig. 4 Structure of reverse supply chain flow of Germany (GER) returns

shafts are transported directly to the supplier's industry for remanufacturing in the full container load mode of shipment. In the less-than-container load mode of shipment, it again undergoes custom clearance in Chennai and is sent to its respective customer freight station. Figure 15b in Appendix 3 shows that inside the customer freight station deconsolidation of the cargo is executed, and the shipments are sorted based on their delivery addresses. After segregation, the shafts are transported from the port to the supplier industry in Chennai. Once the stator shafts are received by the supplier company, the material return note and good return note are generated which are essential for receiving returns. Thereafter, the shaft components are moved to the rework area and the employees inspect the re-manufacturability of the received shafts. If a component is not fit to be remanufactured, it is sent either to the recycling unit for recycling or sent as scrap. As soon as the shaft components pass the inspection, it is sent for remanufacturing. The remanufacturing processes include serration, facing deburring, magnetic particle inspection, outer diameter grinding, polishing, and final inspection. After remanufacturing, if the component passes the quality inspection, it is sent for washing before packing and shipment. If the component fails to pass the quality inspection, it is sent for recycling as shown in Fig. 16 in Appendix 3.

Route module transfers an entity to a specified station or the next station in the station visitation sequence defined for the entity. The transfer time of an entity from one station to its destination entity is fed into the route module using an expression. Figure 17a, b, c, d, e, f, and g in Appendix 3 shows histogram distributions obtained by plotting the collected data set for shipping time to the frequency of the time taken. Each of these histograms depicts the transfer times of shafts from one specific station to a destination station. These plots are subjected to goodness fit tests and a good fit expression for the respective data distribution has been obtained. Goodness fit tests are a type of hypothesis testing and the good fit expression thus obtained is used as the transfer time expression in each route module of the simulation (Ravichandran et al., 2020). Additionally, Table 3 summarizes the expression obtained from the Arena analyzer using a series of goodness fit tests on the data distribution of the transfer times for each of the route modules. The expressions that have been obtained from the analyzer are directly fed into the simulation route modules.

6 Model verification and validation

The developed model was verified to ensure that the conceptual model is reflected by the simulation model representation. The structure, basic outputs, and animated flow of the simulation were reviewed with the case company executive multiple times, thus helping in verification and establishing the credibility of the model. The validation is performed by comparison between simulation and calculated results of transportation time per entity and cycle time per entity as shown in Table 4, Table 5, Table 6, Table 7, and Table 8.

Table 8 shows the estimate of the expected number of returns that should be undergoing each process by the case company and it is used to verify that the simulated model is working the way it is intended. The validation is done by comparing the accepted real system to the model. While Table 4 and Table 5 compare the transportation time in transporting cargo from one station to the respective location, Table 6 and Table 7 compare the cycle times associated with each process in each station separately. Although there are slight deviations observed in the comparisons, the percentage error is less than the accepted level of error of 5%. To ensure that the model data precisely represent the real process, and enhance model validity, a confidence interval analysis was executed. A 95% confidence interval was established, and the number of simulation runs needed was found out by Eq. 1; therefore, the number of replications was performed to achieve the confidence interval (Kelton & Law, 1983).

$$n = \frac{Z_{\alpha/2}^{2}\sigma^{2}}{d^{2}} \text{ (Kelton \& Law, 1983)} \tag{1}$$

where z refers to the critical value from the standard normal table at the respective confidence interval, σ refers to desired standard deviation, d refers to the margin of error expressed, and n refers to the desired replication number.

7 Results and discussion

The model built was simulated for several cases in a particular return type. The total value-added time in the reverse supply chain has been categorized for each return type to address the quality of the reverse supply chain. Subsequently, the wait time per shaft entity is analyzed for each process to find bottlenecks for improvements in the remanufacturing process. The resources that aid the manufacturing process and can be improved were identified. These processes were optimized using the Arena process analyzer for zero wait time. The break-even analysis has been carried out between full container load and less than container load concerning the cost spent on shipment. The breakdown of the total costs involved in the reverse supply chain in both countries has been outlined. Conclusively, the carbon emission and cost related to transportation in the reverse supply chain were estimated. The input return data for simulation were scheduled using 50 case data generated. The return data were classified into three cases low returns, average returns, and high

Table 3 Summary of route expression along with parameters (Chi-square test)

Route	Expression	Corresponding *p-value*
GER customer, to supplier warehouse, GER	TRIA (2.33, 3.63, 4.37)	0.75
US customer to supplier warehouse, USA	UNIF (8.5, 14.5)	0.75
Warehouse, USA to Port of Charleston USA_FCL & Warehouse USA to CFS USA_LCL	32.5 + 14 * BETA (0.912, 1.15)	0.725
Warehouse, GER to Port of Hamburg GER_FCL & Warehouse USA to CFS USA_LCL	TRIA (5.65, 6.26, 6.76)	0.721
US port to Chennai Port	TRIA (40.5, 45, 49.5)	0.75
GER port to Chennai Port	TRIA (24.5, 30, 35.5)	0.55
Chennai port to Company Chennai & CFS_CHN to Company Chennai	NORM (9.68, 1.79)	0.717

returns from the customer. Fill rate is a metric that gives a notion of the number of returns that are shipped from the customer to the supplier. Figures 5a, b, 6a, 6b, 7a, and 7b depict fill rate of returns case-wise for each customer.

In both scenarios irrespective of less than container load, full container load, and return cases transfer times of returned shafts from the USA and Germany are found to be steady and with values ranging between 1104.5 ± 2.5 h and 740.45 ± 2.5 h, respectively. The comparison between the transfer time of returns from both countries is represented in Fig. 17 in Appendix 4. While comparing the average of the essential times (i.e., value-added time) and the non-essential time (i.e., the non-value-added time) per entity, the values have shown a steady difference in each case. For an entity in each scenario as depicted in Fig. 8, it can be noticed that essential time is increased and the non-essential time is decreased as the number of returns are lower. It can be also observed that for a particular return case both the essential and non-essential time of less than container load is slightly greater than full container load.

In the case of remanufacturing, both full container load and less than container load have the same processes and returns in each return case. Both full container load and less than container load yield the same results in remanufacturing wait time, and it is represented in Fig. 9a, b, and c with high, average, and low return cases, respectively.

As shown in Fig. 9, the average wait time per entity is observed to be higher in certain manufacturing processes irrespective of the return cases. In this way, the bottleneck in remanufacturing is found in three processes majorly that are packaging, segregation of shafts, and serration facing deburring processes. Optimization of these processes using the number of resources is prominent for enhanced remanufacturing. Therefore, a process analyzer is used for finding the optimum number of resources for each process. The average return case is chosen for the process analysis to make sure shafts are remanufactured without waiting as depicted in Fig. 18 in Appendix 4. It can be inferred that the wait time per entity for the serration deburring process during maximum returns is reduced only when four resources are used for the free flow of shafts during remanufacturing processes. It can be also inferred from Fig. 19a, b, and c that the

Table 4 Comparison of manual and simulation transport time USA (hours)

To	Warehouse	Port_USA	Port_CHN	Remanufacturer
Manual	12	0.583	1080	10
Simulation	11.5	0.583	1120.2	9.68
Difference	4.1%	0%	3.7%	3.2%

Table 5 Comparison of manual and simulated transport time Germany (hours)

To	Warehouse	Port_GER	Port_CHN	Remanufacturer
Manual	3.4	6.2	720	10
Simulation	3.25	6.39	735	9.74
Difference	4.4%	3%	2%	2.6%

Table 6 Comparison of manual and simulated average process cycle time USA (hours)

In	Customer	Warehouse	Port_USA	Port_CHN	Remanufacturer
Manual	0.1	360	50	24	0.3167
Simulation	0.0954	346.8	51.45	23.05	0.3144
Difference	4.6%	3.6%	2.9%	3.95%	1.68%

Table 7 Comparison of manual and simulated average process cycle time Germany (hours)

In	Customer	Warehouse	Port_USA	Port_CHN	Remanufacturer
Manual	0.134	372	52	24	0.3167
Simulation	0.1294	366	53.5	23.65	0.32
Difference	3%	1.6%	2.8%	1.45%	1.3%

Table 8 Comparison of percentages of shafts in each process-remanufactured, recycled, and scraped (for 1 container, i.e., 10,800 units)

Process	Remanufactured	Recycled	Sent for scrap
Manual	95	4.5	0.5
Simulation	95.167	4.379	0.453
Difference	0.167%	0.121%	0.047%

packaging process needs just three resources and the segregation process requires one more resource; this is represented using a line graph in Fig. 10.

The main difference between full container load and less than container load scenarios exists immensely in their costs of shipment. The cost of shipment for a 20 feet container through full container load does not vary depending upon the no of pallets, while the cost of shipment in less than container load varies accordingly with the volume or weight of the cargo based on whichever is higher. Therefore, for this particular case, a break-even point has been found between freight cost and shipment mode in both countries. The

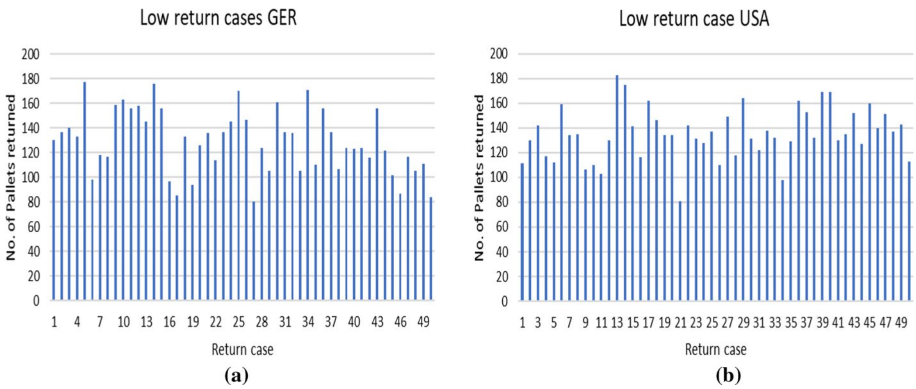


Fig. 5 **a** Fill rate of low returns from GER; **b**. Fill rate of low returns from USA

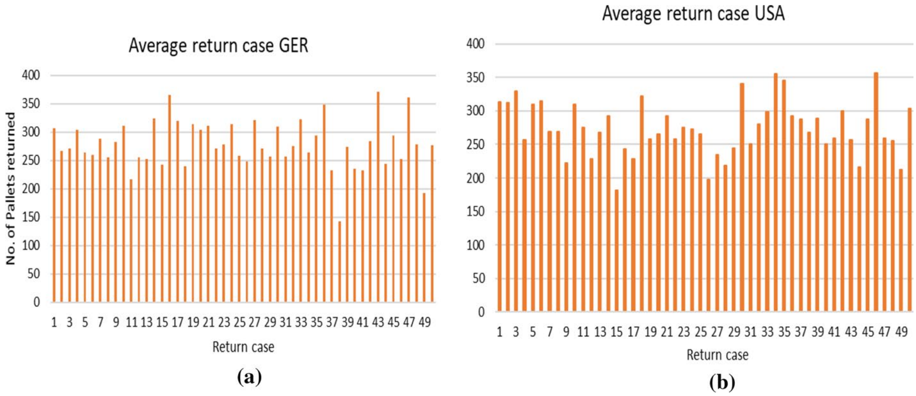
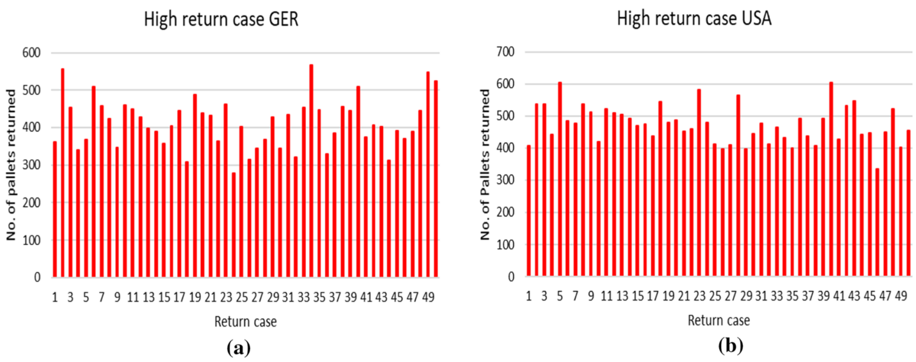


Fig. 6 **a** Fill rate of average returns from GER; **b**. Fill rate of average returns from USA

real-time data by May 2021 is used for this analysis. Depending upon the freight company and seasons, freight charges in full container load may vary therefore maximum and minimum current charges for full container load are considered. Subsequently, the cost of less than container load *vs* the number of pallets is presented graphically in Fig. 20a and b, respectively, in Appendix 4. Thus, it has been found that it is feasible to ship a maximum of 7 pallets in less than a container load from both Germany and the USA.

The breakdown of cost components is presented in Fig. 21a and b in Appendix 4. The components that incur costs in the supply chain are transportation, warehousing, social carbon cost, customs, and remanufacturing. Documentation cost is considered negligible and therefore omitted. Even though there are not any drastic differences, there is a noticeable amount of difference in transportation. Customs account for 4% of the USA while 5% in Germany. The carbon emission responsible for the case of ship freight is calculated using the activity-based approach and the remaining fuel-based approach is used. The emissions calculated are given in Table 9. The social carbon cost of the USA is considerably higher than in Germany. The social cost of carbon is defined as the marginal cost of impacts caused by the emission of one tonne of greenhouse gases at any point in time and the calculation associated with this component is explained in Table 10.



(a) (b)

Fig. 7 **a** Fill rate of high returns from GER; **b**. Fill rate of average returns from the USA

The formulas used in the computation of carbon emissions are:

- Twenty-foot container Equivalent
- $\text{Dieselconsumed} = \text{Distance} \div \text{Mileage}$ (2)
- $\text{Ton} - \text{km} = \text{Ton of Shipment} \times \text{Distance (In full container load} - 9.18\text{ Ton)}$ (3)
- $\text{Metrictoncarbonemission} = \text{Carbonemissionkg} \div 1000$ (4)

Assumptions

$\text{CarbonemissioninLCL} = \text{weight\%} \times \text{CarbonemissioninFullLoad}(5)$

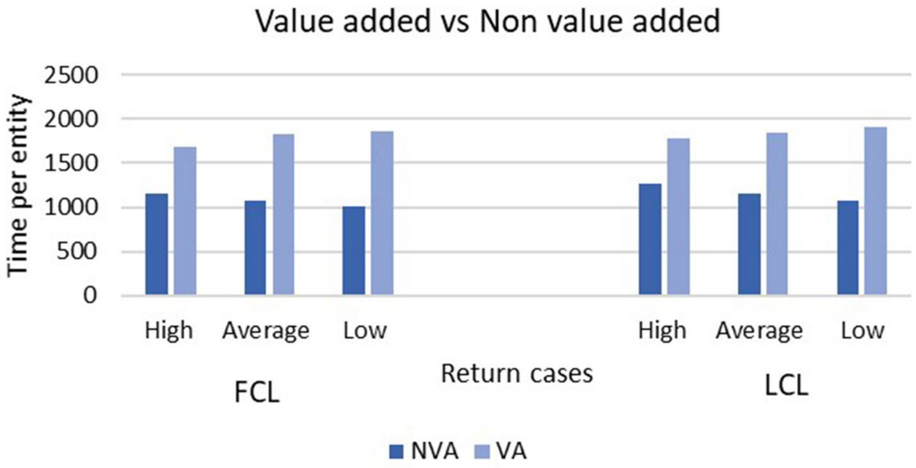


Fig. 8 Value-added Vs non-value-added time

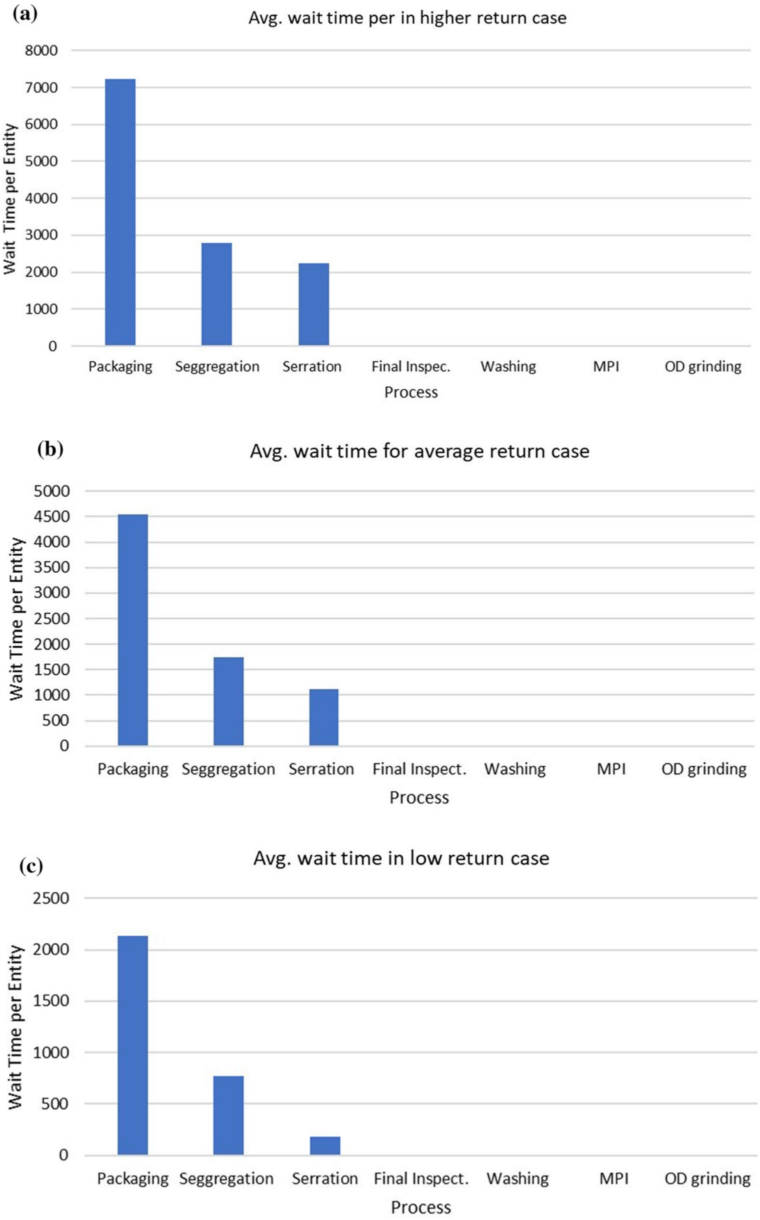


Fig. 9 **a** Average wait time per entity in high return cases. **b** Average wait time per entity in average return cases. **c**. Average wait time per entity in low return cases

In full container load, for a trip from the customer in the USA to the Supplier company in Chennai, carbon dioxide emission is 2.07 Metric tons. For a trip from customer Germany to the Supplier company, carbon dioxide emission is 1.506 Metric tons. Out of 150 return cases for Germany, the highest return and lowest return are chosen to find the range of the carbon emission in each trip and plotted for comparison (refer to Fig. 11a and b).

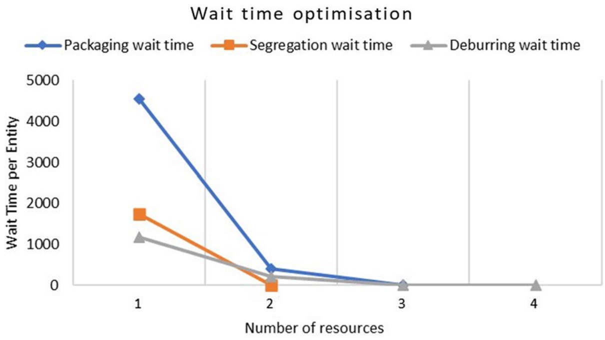


Fig. 10 Wait time per entity optimization

Only the first, 25 trips are considered in each case. Here each case denotes each return (i.e., each trip with a different number of returns). The load ratio is included for approximate carbon emission estimation and sample calculation is provided in Appendix 5.

The total transportation cost associated with the reverse supply chain is summarized in Table 11, and the sample calculation of each mode of transport in each country is shown in Appendix 6.

The total cost associated with transportation in the reverse supply chain if one container of shafts is returned from the German customer to the supplier company is 2799.22 USD approximately 2800 USD. If it is returned by the US customer, the total cost associated with transportation in the reverse supply chain is 2371.85 USD, approximately 2372 USD. Thus, it can be concluded that the cost associated with transportation in the sustainable reverse supply chain of German returns is greater than the cost associated with transportation in the US returns.

8 Implications

8.1 Theoretical implications

The study bolsters the literature by presenting the simulation model of novel manufacturing sustainable reverse supply chains using feasible shipment modes. The entity used in the simulation of the reverse supply chain is the stator shaft which is an automotive part. The study further strengthens the literature by considering two customers from two different countries in the reverse supply chain study. The study also supports the literature by providing different types of return types that can be expected by the customers and analyzing their impact on the sustainable reverse supply chain simulation model.

The model was built using Arena simulation software and simulated to derive results related to supply chain metrics. Likewise, estimations regarding carbon emission and transportation cost per trip in the reverse supply chain were also addressed. The key numerical results can be summarized as follows. In both scenarios irrespective of less than container load, full container load, and return cases transfer times of returns from the USA and Germany are found to be steady at 1104.5 h and 740.45 h, respectively. In full container load, for a trip from the customer in the USA to the Supplier company in Chennai carbon dioxide emission is 2.07 Metric tons while for a trip from customer Germany to the Supplier company, carbon dioxide emission is 1.50 Metric tons. Moreover, the approximate total

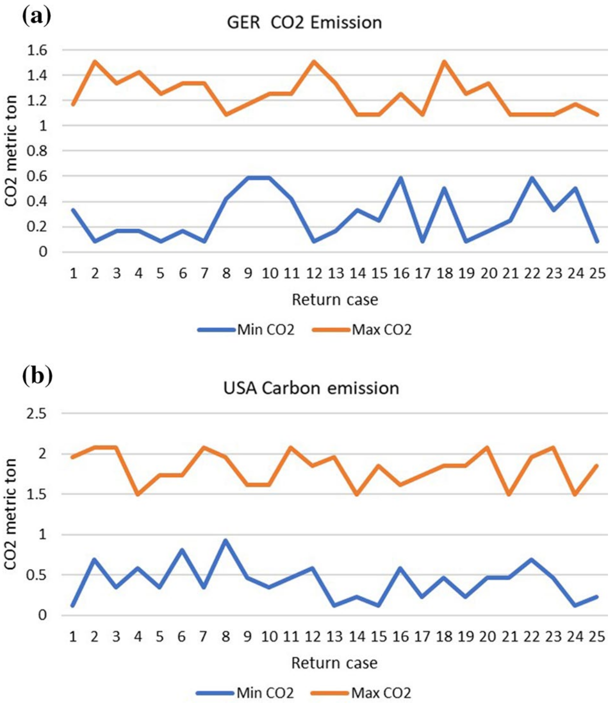
Table 9 Carbon emission tabulation for a full container return

From	To	Dist. (km)	TEU	Mileage (Kmpl)	Diesel (liter)	Ton-Km	Emission Factor (Mathers et al., 2014)	Carbon emission (Kg)	Metric ton
Customer USA	Warehouse USA	1384	–	3.61	383.37	–	–	1027.4	1.027
Warehouse USA	Port of Charleston	54.71	–	3.61	15.15	–	–	40.6	0.04
Port of Charleston	Port of Chennai	16,603	1	–	–	16,603	59.1	981,237.3	0.98
Customer GER	Warehouse GER	350	–	2.89	121.1	–	–	324.54	0.324
Warehouse GER	Port of Hamburg	700	–	2.89	242.21	–	–	649.12	0.649
Port of Hamburg	Port of Chennai	14,008	1	–	–	14,008	36.3	508,490.4	0.508
Chennai Port	Supplier	60	–	6.25	9.6	–	–	25.72	0.0257

Table 10 Cost summary in transportation per trip

From \ To	Distance (km)	Regional Fuel cost/ liter	Fuel Cost (USD)	Driver Cost (USD)	Freight cost (USD)	Social carbon cost (USD) (Ricke et al., 2018)	Total Cost (USD)
GER customer to Supplier warehouse GER	360	1.54	192.90	301.59	–	− 1.71	299.88
GER warehouse to GER Port	700	1.54	375	210.50	–	− 3.27	582.22
GER Port to CHN Port	–	–	–	–	1875	25.42	1900.42
USA customer to Supplier Warehouse USA	1384	0.81	313.60	412.80	–	49.1	775.5
USA warehouse to USA Port	54.7	0.81	12.40	16.32	–	1.94	30.6
USA Port to CHN Port	–	–	–	–	1500	49.06	1549.06
CHN Port to Supplier Company	65	1.13	11.82	2.68	–	2.19	16.69

Fig. 11 **a** Carbon emission range GER **b**. Carbon emission range USA



transportation cost in the reverse supply chain if one container of shafts is returned from the German customer to the supplier company is approximately 2800 USD while the US returns its 2370 USD. The study has also included social carbon costs incurred in transportation which is a significant contributor to sustainability measurement. The total social carbon cost associated with the per trip transportation in returns from Germany and the USA is found to be 20.43 USD and 100.10 USD, respectively. Social carbon cost being a measure of economic damage due to one-tonne carbon emission confirms that Germany has little harm to its economy than the USA in deploying the reverse supply chain. The results show that the proposed model addressed the literature gaps by simulation modeling a sustainable reverse supply chain using a manufacturing automotive part and provides the contribution of the study to the literature. Further, the reported study is expected to motivate research on sustainable reverse supply chains using multiple customers and multiple remanufacturing sites using a manufacturing case study.

8.2 Managerial implications

The sustainable reverse supply chain model using Arena simulation has been modeled with the use of data collected from the case organization. It has also been verified by the case organization executives and validated. The outcomes of different modes of transport available and multiple return cases on the sustainable reverse supply chain model have also been acknowledged. The working and analysis of the sustainable reverse supply chain in a manufacturing industry comparable to the real-world application have been performed. The proposed model serves as a reference in the execution of the reverse supply chain in the real world. It also provides the opportunity for additions to the model according to the current situation.

The study also provides an awareness of several resources and energy that are required to successfully accommodate the returns. Thus, the study aids in decision-making for the preparation of the warehouses and remanufacturing arena. A demo sustainable reverse supply chain implementation has been carried out by the case organization with one full container load return from a German customer. It is observed that the factors such as transfer time, wait time per entity, total lead time and transportation costs are well within the estimated range values. The organization is satisfied with the outcome and engaged in adapting for the better. They are also interested and involved in finding options to reduce carbon emissions as well as the costs associated with the reverse supply chain.

9 Conclusion

The reverse supply chain in India is irregular and does not follow a framework. This study addresses and streamlines the working of the reverse supply chain in the manufacturing industry, develops a simulation model similar to the real-world application of the reverse supply chain, and discusses the scenarios associated with the reverse supply chain model. The novelty of the study is to build a reverse supply chain using a particular case study of an organization considering its customers offshore and products manufactured by the organization. It is also important to note that, there exists limited investigation on reverse supply chain modeling through simulation methodology and almost negligible that deals with the simulation of manufacturing organization reverse supply chain. This study, therefore, proposes a possible reverse supply chain framework that could be adopted by different manufacturing industries, and yield opportunities for performance improvement.

The study demonstrates various metrics related to the sustainable reverse supply chain model for a particular case company with consideration of environmental and economic perspectives. Initially, a conceptual framework of the sustainable reverse supply chain using the processes involved was outlined. Then, the model was built with the use of several modules available in Arena simulation software. The economically feasible transport modes full container load and less than container load was integrated into the study. Return cases were categorized as low, medium, and high return cases. In this paper, Arena simulation has been established using two different modes of shipment scenarios. This model has been developed using the data collected from the forward supply chain and using the expected fill rates for each return case. Histograms were plotted based on the data collected and good fit expressions were obtained for using it in route modules of the simulation. The comparison between both scenarios was carried out and significant parameters of reverse supply were discussed for each type of return case. The effect of modes of transport and return cases were highlighted in value-added *vs* non-value-added comparisons and average wait time graphical comparison. The working of a reverse supply chain in the manufacturing industry was presented using several processes in each stage of transportation and remanufacturing. The study contributes uniquely to the literature by highlighting the prominent factors of a reverse supply chain such as expected fill rates, transfer time from each customer to the supplier company, comparison between Value-added and non-value-added time, and wait time per entity. Additionally, economic estimation along with the inclusion of sustainable factors was executed. The findings reveal that the average transfer time for the returns from US customers to Chennai and German customers to Chennai is obtained as 1104.5 ± 2.5 h and 740.45 ± 2.5 h, respectively. Additionally, the bottleneck in the remanufacturing process using wait time per entity is found. Individual resource optimization for zero wait time for the respective resource has been executed using a process analyzer. The carbon emission associated with the transportation of the whole sustainable reverse supply chain model has been calculated using mixed methods of activity-based approach and fuel consumption-based approach. The carbon emission per trip of full container load quantity of returns from the USA to Chennai is estimated as 2.07 Metric tons while from Germany to Chennai it is estimated at 1.50 Metric tons approximately. It can be observed that the emission in transportation from the USA is greater than the carbon emission involved in transportation from German returns. The breakdown of the cost involved with the model has also been graphically illustrated with the inclusion of the social cost of carbon which is rarely addressed in existing literature. Finally, the transportation cost was calculated to give an estimate of the cost associated with transport per trip for the USA and German returns with the inclusion of social carbon cost. The transport cost of USA and German returns are found to be 2372 USD and 2800 USD, respectively. In contrast to the carbon emissions, it is observed that the transport cost for German returns is higher for a trip than the return from the USA.

9.1 Limitations and future scope

The case organization has warehouses in several locations across the globe. The already existing warehouses even though proved to be useful, have limited the study from optimizing the warehouse location for the optimal sustainable reverse supply chain. Therefore, future studies can use cases where warehouses were not present in customers' countries and deal with the optimization of international manufacturing warehouse locations for better sustainable reverse supply chain implementation and distribution. If possible, a similar study with the replacement of the case entity with another manufacturing product that might be returned because of various physical factors can be carried out. Thus, considering a different set of remanufacturing processes for each defect, the feasibility of a reverse supply chain can be checked. In continuation to the estimation of carbon emissions and costs associated with transportation, future studies can focus on the effective reduction of transportation costs and carbon emissions in the reverse supply chain alone. Moreover, studies can use the concept of air freight transport and analyze its merits and demerits. In the future, domestic manufacturing companies with inland customers can be considered for sustainable reverse supply chain simulation and identification of improvement areas. Furthermore, the inclusion of industry 4.0 concepts in the reverse supply chain of the manufacturing industry to enhance sustainable closed-loop supply chains can be explored.

Appendix

Appendix 1

Need for reverse supply chain by economic estimation.

Customer's perspective

Remanufacturing of stator shafts is economically viable in India rather than remanufacture them almost in any abroad countries especially in customers' sites. The economic perspective of the customer is shown using a simple calculation for remanufacturing the number of products that fit a 20 ft container, i.e., 18 pallets of stator shafts.
Each pallet can accommodate around 600 stator shafts.
Therefore, 18 pallets can accommodate = 18 × 600 = 10,800 shafts.
Total Lead time of deburring, OD grinding, inspection = 3.5 min.
Total process time for 10,800 shafts = 10,800 × 3.5 = 180 h.
Cost of Labour for 1 h = 23 USD.
Total labor cost = Total no of labour × Total working hours × labor cost per hour = 4 × 180 × 23 = USD 16,560.
Machine hour rate = 70 USD Total machine cost = Machine hour rate × Total working hours = 70 × 180 = 12,600 USD For four machines = 12,600 × 4 = 50,400 USD.
Therefore, total cost = Total Labor cost + Total Machine cost = 66,960 USD.
Freight charges for shipping 20ft container FCL (Full Container Load) cargo from the USA to India = 1300 USD to 2000 USD depending on factors such as time, season, etc. Therefore, it can be said only 1600 USD will be spent by the customer as freight charges and around 65,000 USD will be saved by the customer if they decide on remanufacturing in India.

Overall economic perspective

In India, the machine hour rate would be around Rs. 200.
Total Machine cost = Total working hours × labor cost per hour = 200 × 180 = Rs. 36,000.
For 4 resources = 4 × 36,000 = Rs. 1, 44, 000.
Labor cost per hour in India = Rs. 20 Therefore for 180 h = Total working hours × labor cost per hour = 180 × 20 = Rs. 3,600 For 4 labors = Rs. 3600 × 4 = Rs. 14,400.
Total cost = Total Machine cost + Total labor cost.
= Rs. 1, 44, 000 + Rs. 14,400 = Rs. 1,58,400 i.e., 2114.98 USD.

Appendix 2

See Table 11.

Table 11 Difference between FCL and LCL

FCL	LCL
FCL prefers higher volume goods	In LCL, smaller volumes of transport are preferred
FCL cost lesser than LCL	The transportation cost per unit is higher in LCL
Goods through FCL are delivered more quickly	LCL is delayed due to these additional processes
	Consolidating different shipments,
	Processing multiple documents per container, and
	Sorting goods for each customer

Appendix 3

See Figs. 12, 13, 14, 15, 16 17 and 18.

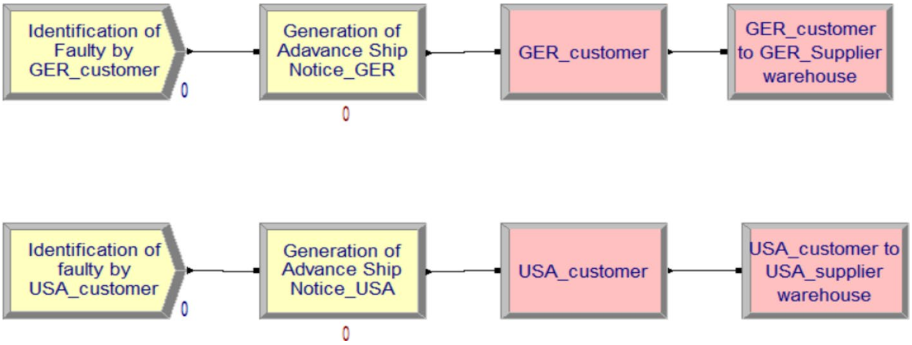


Fig. 12 Customer identification in GER and USA-FCL & LCL

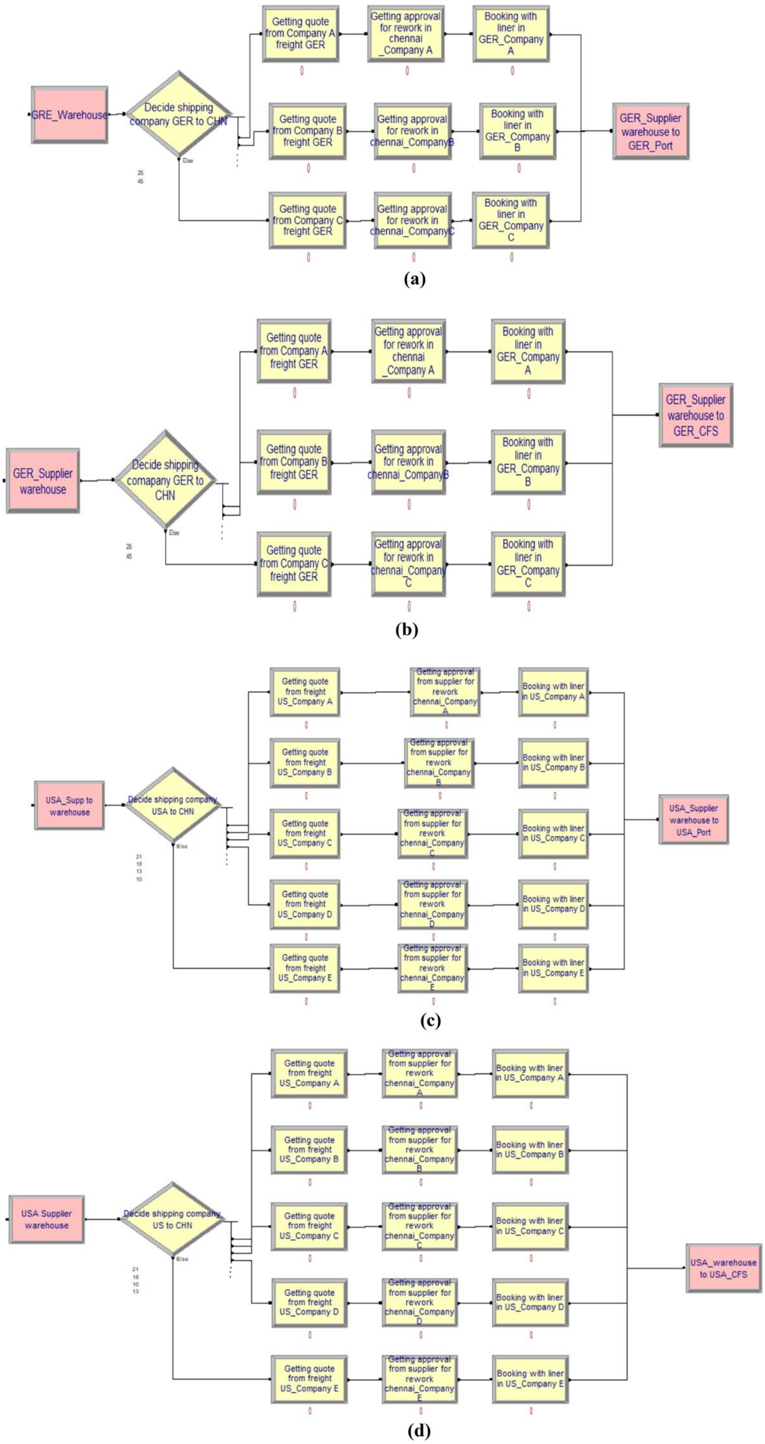


Fig. 13 **a** Deciding freight forwarder Germany-FCL. **b** Deciding freight forwarder Germany–LCL. **c** Deciding freight forwarder USA–FCL. **d** Deciding freight forwarder USA–LCL

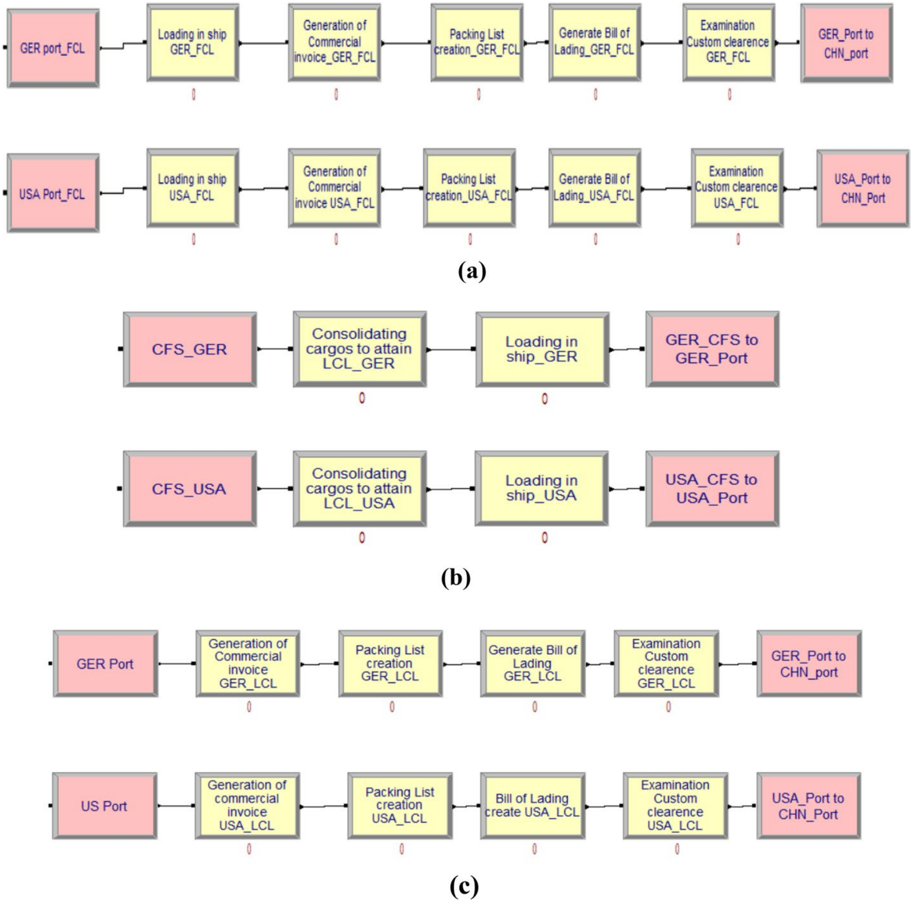


Fig. 14 **a** Processes in port in Germany and USA–FCL. **b** Container freight station in Germany and USA–LCL. **c** Process in port in Germany and USA–LCL

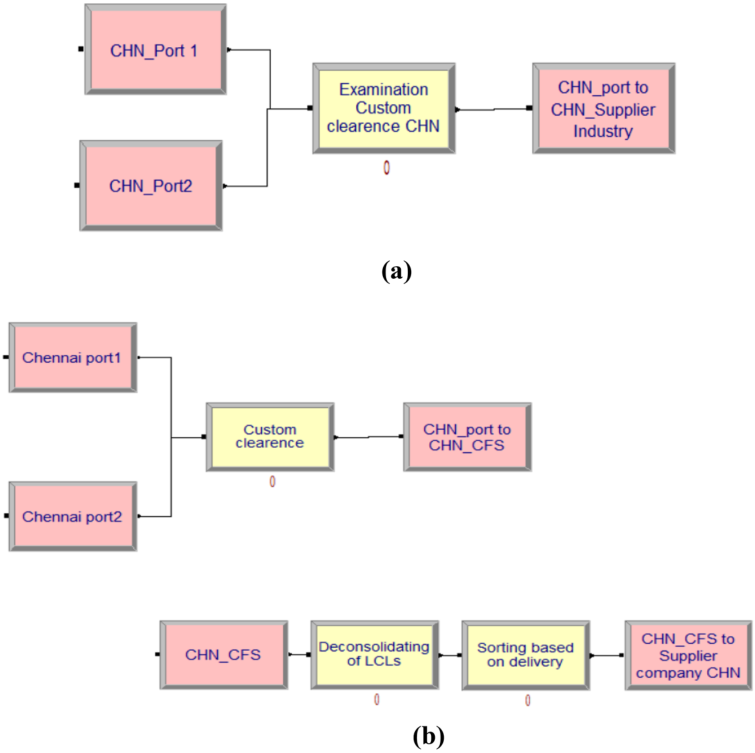


Fig. 15 **a** Customs clearance Chennai CHN–FCL. **b** Customs clearance and container freight station Chennai (CHN) –LCL

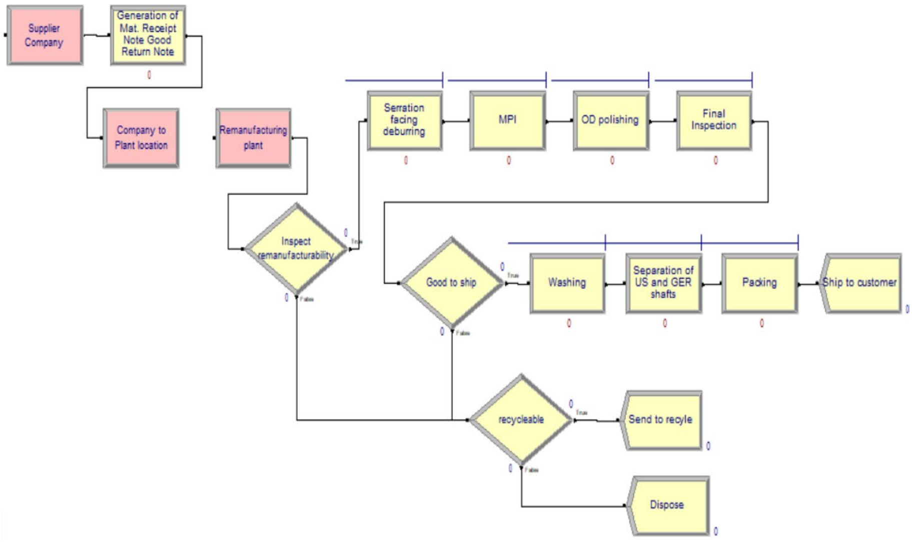
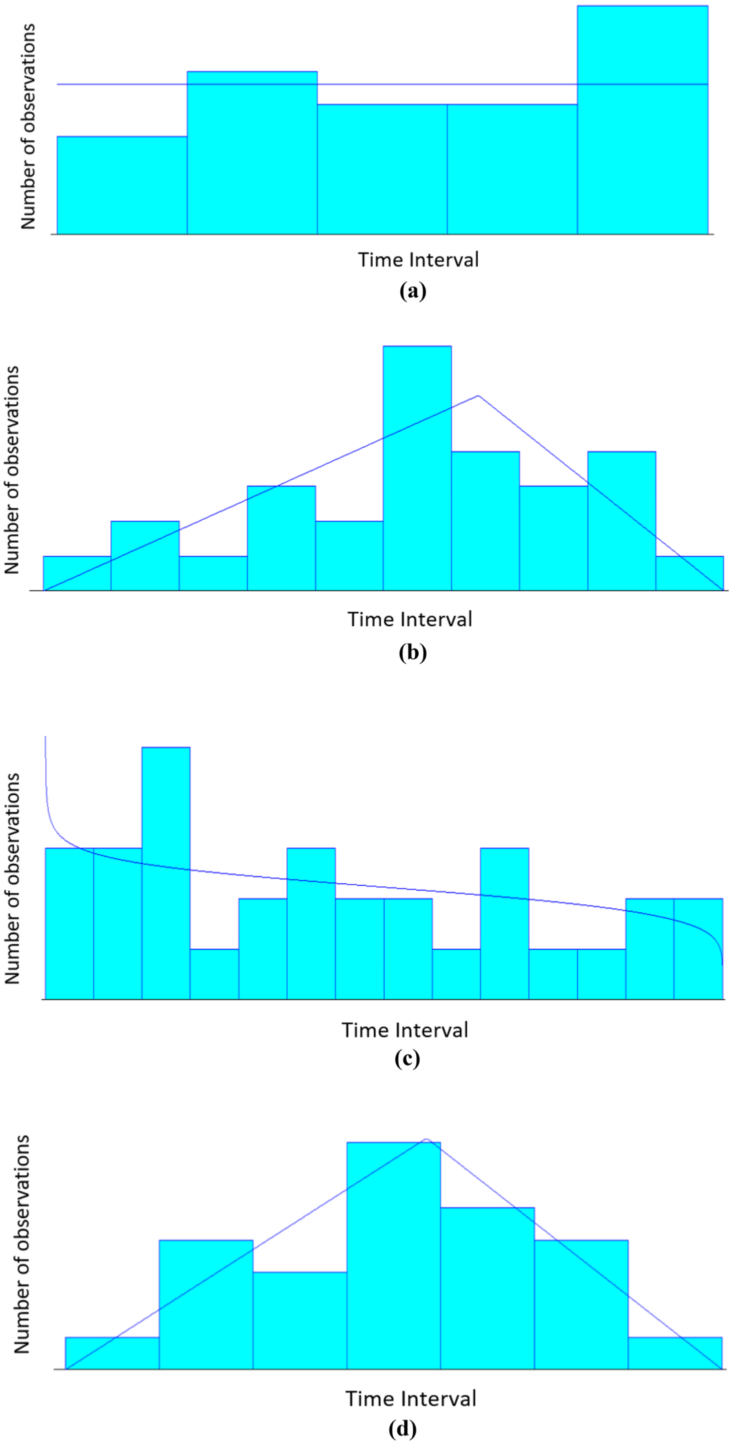


Fig. 16 Remanufacturing process in supplier industry


Number of observations
Time Interval
(a)
Number of observations
Time Interval
(b)
Number of observations
Time Interval
(c)
Number of observations
Time Interval
(d)

◀ **Fig. 17** **a**. Transfer time from USA customer to supplier warehouse in USA. **b**. Transfer time from GER customer to supplier warehouse in GER. **c** Transfer time from warehouse USA to port of Charleston USA. **d**. Transfer time from warehouse, GER to port of Hamburg GER. **e**. Transfer time from USA port to CHN port **f**. Transfer time from GER port to CHN port **g** Transfer time from Chennai port to case company Chennai

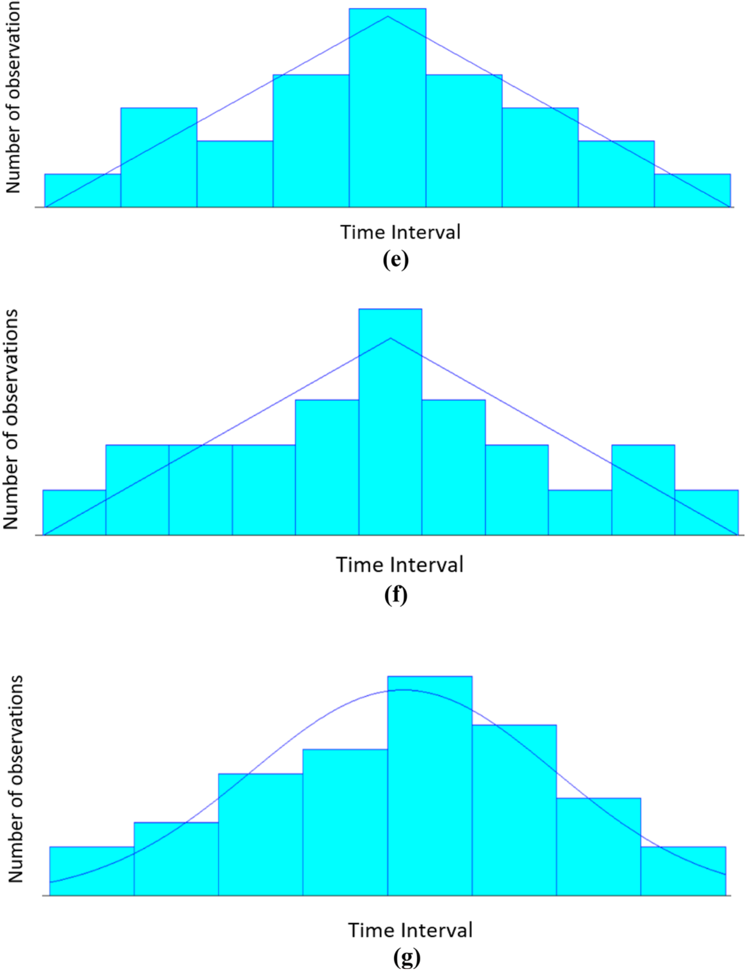


Fig. 17 (continued)

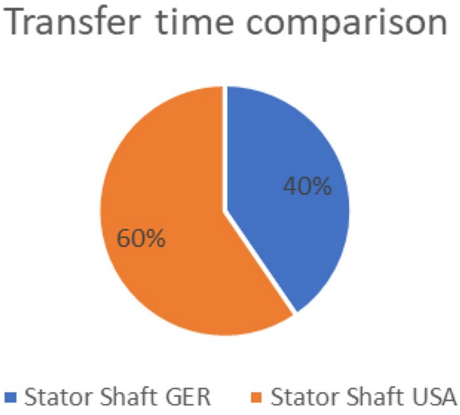
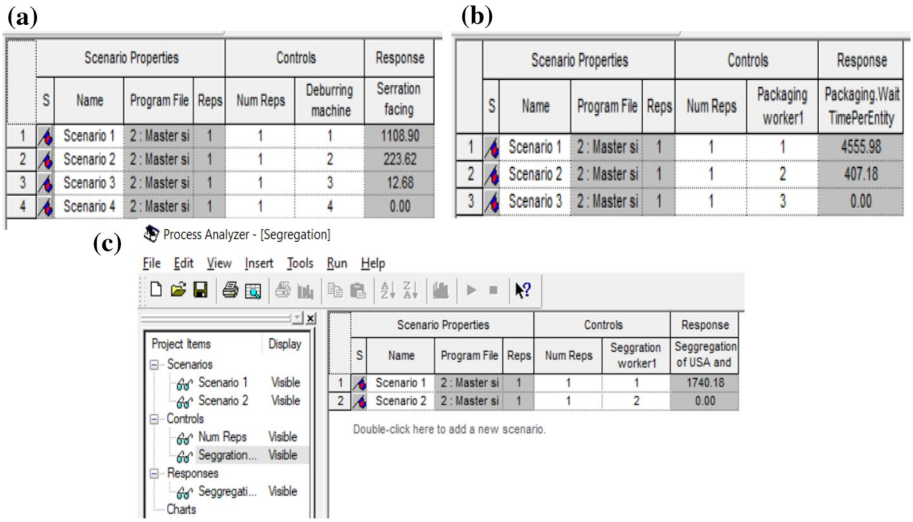


Fig. 18 Transfer time comparison between shafts from both customers

Appendix 4

See Figs. 19, 20 and 21.



(a)

	Scenario Properties				Controls		Response
	S	Name	Program File	Reps	Num Reps	Deburring machine	Serration facing
1		Scenario 1	2 : Master si	1	1	1	1108.90
2		Scenario 2	2 : Master si	1	1	2	223.62
3		Scenario 3	2 : Master si	1	1	3	12.68
4		Scenario 4	2 : Master si	1	1	4	0.00

(b)

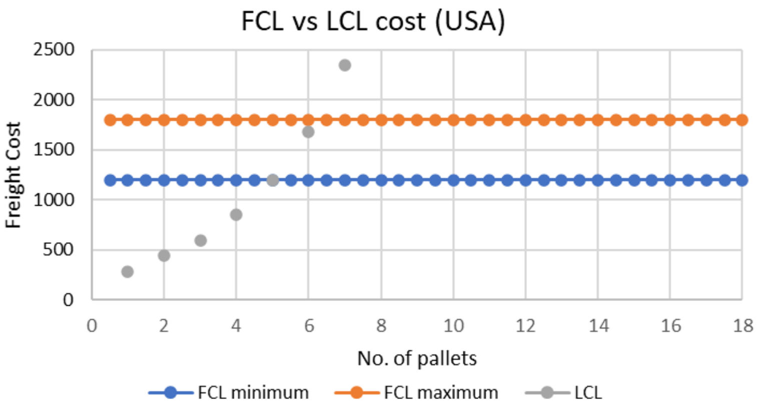
	Scenario Properties				Controls		Response
	S	Name	Program File	Reps	Num Reps	Packaging worker1	Packaging.Wait TimePerEntity
1		Scenario 1	2 : Master si	1	1	1	4555.98
2		Scenario 2	2 : Master si	1	1	2	407.18
3		Scenario 3	2 : Master si	1	1	3	0.00

(c)

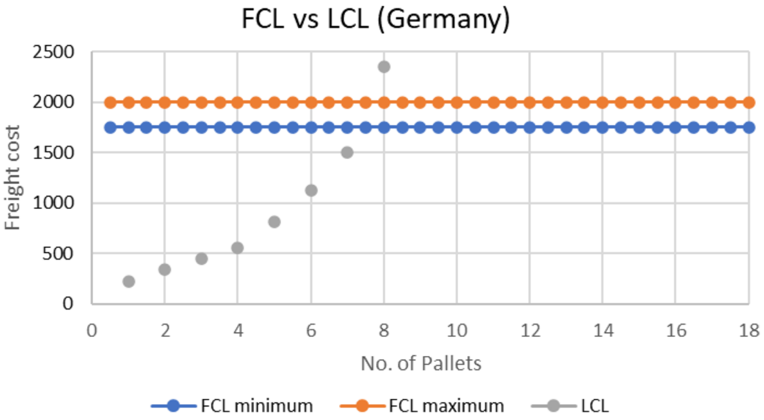
	Scenario Properties				Controls		Response
	S	Name	Program File	Reps	Num Reps	Seggration worker1	Seggregation of USA and
1		Scenario 1	2 : Master si	1	1	1	1740.18
2		Scenario 2	2 : Master si	1	1	2	0.00

Double-click here to add a new scenario.

Fig. 19 **a**. Process analyzer for serration deburring process; **b**. Process analyzer for packaging process; **c**. Process analyzer for segregation process.



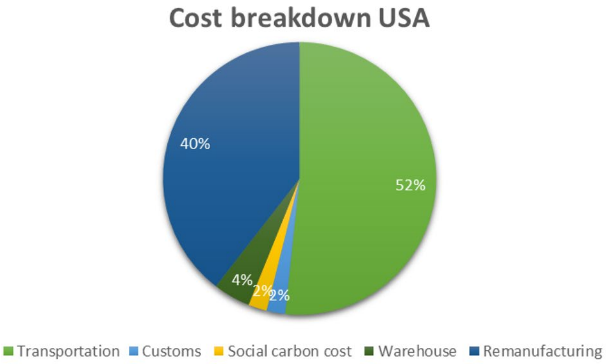
(a). FCL vs LCL freight cost USA



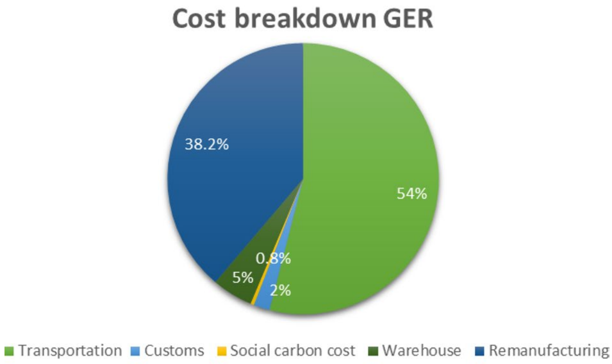
(b). FCL vs LCL freight cost GER

Fig. 20 **a**. FCL versus LCL freight cost USA **b**. FCL versus LCL freight cost GER

Fig. 21 **a** Pie chart of cost breakdown-USA. **b** Pie chart cost breakdown–GER



(a). Pie chart of cost breakdown- USA



(b). Pie chart cost breakdown – GER

Appendix 5

Sample calculation of carbon emission

If 6 pallets are being shipped by any mode of shipment from USA.
No. of shafts accommodated in 6 pallets $= 6 \times 600 = 3600$.
Weight of one shaft $= 0.85$ kg.
Weight of 3600 shafts $= 3600 \times 0.85 = 3060$ kg.
No. of pallets in 1 container $= 18$.
No, of shafts in one container $= 18 \times 600 = 10{,}800$.
Weight of one container shafts $= 10{,}800 \times 0.85$ kg $= 9180$ kg.
Ratio of load compared to full container case $= 3060 / 9180 = 0.333$.
Therefore, it is approximated that.
Carbon emission shipping 6 pallets $= 33.33\%$ of carbon emission of full container load USA.
$= 0.33 \times 2.07 = 0.69$ Metric ton of CO_2.

Appendix 6

Calculation by April 26, 2021. Sample calculation of each mode of transport in each country is shown below.

Customer Germany to warehouse at Germany

Distance per trip = 360 km.
On an average 2.89 km run per liter diesel in Germany.
Therefore 124.56 L required.
Cost per liter in Germany = Euro 1.28 = 1.54 USD.
For 124. 56 L = 1.54 × 124.56 = = 192.9 USD.
Driver cost = 0.4 Euro per mile = 0.4 × 223.7 = 89.84 Euro = 108.7 USD.
Metric ton of Carbon emission = 0.34 ton.
Social carbon cost of Germany = -5.05 USD/tonne $CO_2 = -5.05 \times 0.34 = -1.717$ USD.
Total cost = Fuel cost + Driver cost + Social carbon cost = 192.9 + 108.7–1.71 = 299.88 USD.

Port of Hamburg to port of Chennai

Fuel cost is not considered.
Freight charges for 20ft container on average = 1500 USD.
Metric ton of carbon emission = 0.50849 ton Social carbon cost central estimate = 50 USD/tonne $CO_2 = 50 \times 0.50849 = 25.425$ USD.
Total cost = Freight cost + Social carbon cost = 1525.425 USD.

Port of Charleston to port of Chennai

Fuel cost is not required.
Freight charges for 20ft container on average = 1875 USD.
Metric ton carbon emission = 0.9812373 ton.
Social cost central estimate = 50 USD = 50 × 0.9812373 = 49.06 USD.
Total cost = 1924.06 USD.

Customer USA to supplier warehouse USA

Distance = 860 miles = 1384 km.
Fuel consumption = 3.61 km per liter.
So, 1384/3.61 = 383.37 L is required.
Cost per liter diesel = 0.818 USD per liter.
Therefore, 383.37 × 0.818 = 313.6 USD.
Driver cost = 0.48 USD per mile = 0.48 × 860 = 412.8 USD.

Metric ton of Carbon emission = 1.027 ton.
Social carbon cost in USA = 47.8 USD / tonneCO_2 = 47.8 × 1.027 = USD 49.1
Total cost = 313.6 + 412.8 = 726.4 + 49.1 = 775.5 USD.

CHN port to supplier company

Truck mode–Uses diesel.
Distance per trip = 65 km.
16 tonne Truck runs for 6.25 km per liter diesel.
Therefore 10.4 L required.
Cost per liter in Chennai = Rs. 85.
Fuel cost = Rs. 10.4 × 85 = Rs. 884 = 11.82 USD.
Also, Driver cost = Rs. 200 (approx.) = 2.6755 USD.
Metric ton carbon emission = 0.025728 ton.
Social carbon cost of India = 85.4 USD / tonneCO_2 = 85.4 × 0.025728 = 2.197 USD.
Total cost per trip = 11.82 + 2.6755 + 2.197 = 16.697 USD.

Data availability All data generated or analyzed during this study are included in this published article [and its supplementary information files].

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