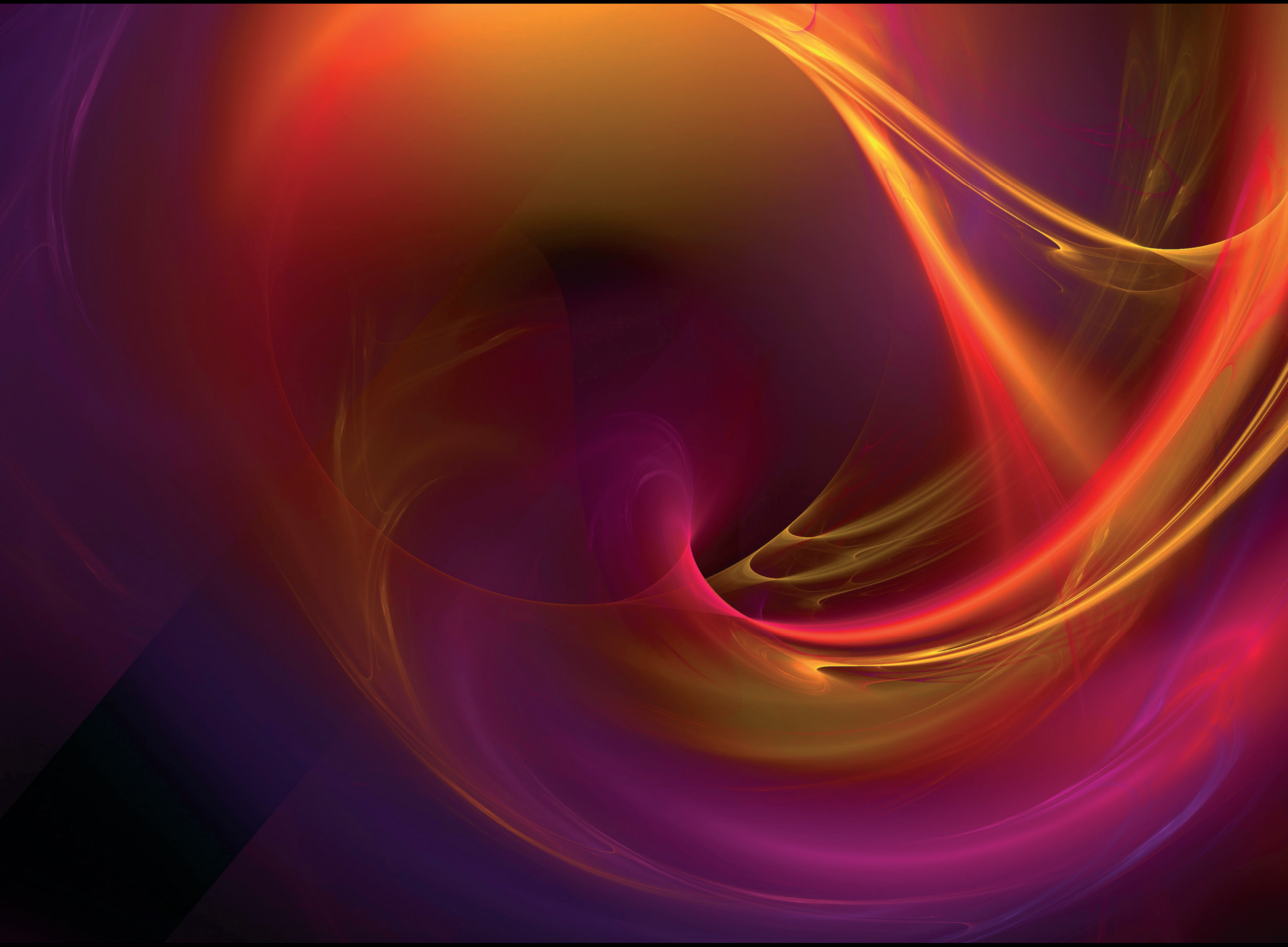
Complexity

Evolving Trends in Supply Chain Management: Complexity, New Technologies, and Innovative Methodological Approaches

Lead Guest Editor: Salvatore Cannella
Guest Editors: Roberto Dominguez, Jose M. Framinan, and Borja Ponte



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Editorial Board

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Editorial

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Supply chain management has become one of the primary key success factors to deal with the increasing *complexity* of the current business environment [1, 2]. Although supply chain management is a mature discipline, the complexity of actual supply chains has greatly evolved over the last two decades [3–5] due to the dynamic interaction of a wide range of processes, decisions, and structures, whose understanding becomes essential for gaining a competitive advantage in the marketplace. Indeed, most supply chain management research has focused on the assumption of linear relationships between nodes buyers and suppliers. However, these supply chains are no longer linear systems, but are characterized by network structures with autonomous and heterogeneous members [6]. As a result, the Operations Management community is currently rethinking on celebrated concepts and largely accepted ideas, with the aim of developing new theory that better captures the requirements of this organizational scene.

New technologies have also played a key role in the aforementioned evolution of supply chains [7]. Continuous technological developments, such as augmented reality, direct digital manufacturing, warehouse automation, and 3D printing [8, 9]—to name a few—open a new world of opportunities from a supply chain perspective. These new technologies not only allow increasing the efficiency and flexibility of manufacturing and distribution processes, but also modify the relationship between the different echelons of the supply chain, with a special emphasis on the consumer. For this reason, the use of these technologies has been deemed as one of the key tools for firms to enhance their competitiveness and to build up their relationships with up- and downstream supply chain nodes. Accordingly, the applications of these technologies for supply chain management have become a fruitful area of research, given its clear and strong managerial implications.

Overall, all these opportunities and challenges currently emerging emphasize the need for fostering *innovative methodological approaches* in supply chain research [10]. Decision-makers need to be equipped with methodological frameworks that enable them to gain understanding on the different problems and to facilitate the finding of robust solutions. In this regard, several methodological approaches, such as agent-based modelling and fuzzy control systems, have proven to be instrumental laboratories for supply chain analysis and decision-making [11, 12]. In this manner, methodology, together with complexity and technology, becomes the third strategic axis of this special issue aimed at disseminating emerging developments in the supply chain area.

Reflecting on these three axes, this special issue brings together five high quality research works exploring the new challenges and proposing new solutions for modern supply chains. We note that each submission was evaluated through a blind-review process, where at least two reviewers, who are experts in their corresponding fields, have assessed the quality of the article. As guest editors, we are very satisfied with the quality of the papers presented in this issue, which contribute to the body of knowledge in this crucial topic for businesses from the three mentioned axes. We briefly describe their contributions below.

Z. Chen, in his paper “The Influence of 3D Printing on Global Container Multimodal Transport System,” evaluates the impact of 3D printing on a container logistics system by developing a system dynamics model of a sneakers' supply chain and establishing a comprehensive index system. The author finds that the aggregate demand for international transport would decline after the application of 3D printing. In addition, the evaluations based on the data of Guangzhou port suggest that the 3D printing of sneakers was not enough to subvert the existing container logistics system. Finally, this research paper concludes that deglobalization caused by 3D printing and globalization strengthening caused by trade cooperation will work together in this container system and lead to more complex changes.

Another work explores the practice of *inventory consignment*, an arrangement where the retailer holds items in its inventory which are still owned by the supplier, as a fruitful mechanism for supply chain collaboration. While the opportunities derived from consignment are well known in terms of supply chain efficiency, it does not come without relevant challenges to be dealt with. In this regard, establishing a fair and robust pricing agreement becomes essential to ensure the long-term viability of this collaborative solution. In light of this, P.-Y. Chen, in the paper entitled “Optimal Retail Price Model for Partial Consignment to Multiple Retailers,” explores the product pricing decision in a supply chain with one supplier and multiple retailers operating under a consignment stock policy. This work proposes a partial product consignment model, where both the seller and the buyers absorb a portion of the inventory costs. Moreover, a relevant feature of this work is a valuable range of managerial implications, which would allow decision-makers to adjust product prices depending on the market fluctuations and sales requirements.

The article “Discrete Switched Model and Fuzzy Robust Control of Dynamic Supply Chain Network,” by S. Zhang et al., investigates a fuzzy robust strategy to accomplish the robust operation of supply chain networks. They consider both production and ordering lead times in a scenario characterized by uncertainty in customer demand. To do so, the authors establish a discrete switched model of the dynamic supply chain network based on Takagi-Sugeno (T-S) fuzzy systems and propose a fuzzy strategy to control the switching actions among subsystems. From this perspective, they show how the proposed fuzzy strategy (consisting of the fuzzy switched strategy and the fuzzy control strategy) can guarantee the robust operation of the supply chain network in a cost-effective manner.

I. Cabral and A. Grilo, in their research “Impact of Business Interoperability on the Performance of Complex Cooperative Supply Chain Networks,” propose an agent-based model for evaluating the effect of business interoperability on the performance of cooperative supply chain networks. After rigorously identifying specific and relevant gaps in the business interoperability literature, they address this question by adopting a multimethod approach which combines empirical data and simulation. More specifically, they first collect data via face-to-face interviews and by analysing the annual reports and newsletters of Valorpneu, which is one of the industrial networks with the best business interoperability performance in Portugal. Later, they populate the agent-based model with these data and perform a “what-if” analysis. As a result, they reveal novel conclusions for the business interoperability field by accurately formalising both theoretical and managerial implications. Finally, they propose interesting new research questions for further analysis in other business network contexts (e.g., automotive and aircraft industries).

D. A. O. Vera et al., in their article “Combined Use of Mathematical Optimization and Design of Experiments for the Maximization of Profit in a Four-Echelon Supply Chain,” propose and employ an innovative methodological approach for designing supply chain networks based on the combination of mathematical optimization and experimental designs. Through these techniques, they address the location of manufacturing facilities and distribution centres, the selection of the appropriate suppliers, and the allocation of the material flow in a four-echelon supply chain. To illustrate their proposal, they evaluate the impact of four main factors (capacity, quality, delivery time, and interest rate) on the operational and financial performance in a case study, showing how this methodological framework allows practitioners to gain understanding on the complex interdependencies that govern the dynamics of supply chains.

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Research Article

Combined Use of Mathematical Optimization and Design of Experiments for the Maximization of Profit in a Four-Echelon Supply Chain

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This paper develops a location-allocation model to optimize a four-echelon supply chain network, addressing manufacturing and distribution centers location, supplier selection and flow allocation for raw materials from suppliers to manufacturers, and finished products for end customers, while searching for system profit maximization. A fractional-factorial design of experiments is performed to analyze the effects of capacity, quality, delivery time, and interest rate on profit and system performance. The model is formulated as a mixed-integer linear programming problem and solved by using well-known commercial software. The usage of factorial experiments combined with mathematical optimization is a novel approach to address supply chain network design problems. The application of the proposed model to a case study shows that this combination of techniques yields satisfying results in terms of both its behavior and the obtained managerial insights. An ANOVA analysis is executed to quantify the effects of each factor and their interactions. In the analyzed case study, the transportation cost is the most relevant cost component, and the most relevant opportunity for profit improvement is found in the factor of quality. The proposed combination of methods can be adapted to different problems and industries.

1. Introduction

The first aim of this research is to provide a mathematical model to optimize a supply chain network by maximizing the system profit, in which the performance of its solution is evaluated depending on changes observed in different levels of capacity, quality, delivery time, and the interest rate, four interrelated relevant aspects. The proposed model is applied to a supply chain that is composed of r suppliers that deliver m raw materials to f manufacturers, who ship p products to d distribution centers, which finally send them to c customers, as shown in Figure 1. The model optimizes the supply chain network yielding the highest benefit, taking into account demands and costs under a deterministic scenario, where all materials and products flowing through the supply chain can be represented by continuous amounts, and the optimization is made for a single time period. It is worthy to mention that optimization models can be solved using different techniques depending on the computational complexity of the model and the instance. The model proposed in this paper involves an NP-hard structure because of the decisions to locate operations at each level of the supply chain. The most direct approach is using commercial software that applies mathematical programming, which is limited to solving small or medium size instances for NP-hard problems. To solve larger instances, in many cases the use of metaheuristics like

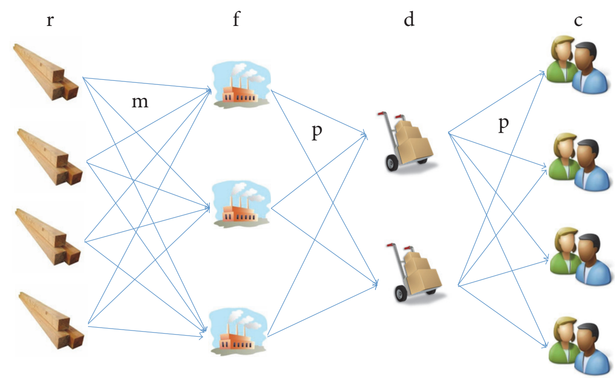


Figure 1: Structure of the analyzed supply chain (source: own elaboration).

the Black Hole Algorithm [1] or Evolutionary Algorithms [2] or others [3] is necessary.

One relevant novelty of this proposal is the integration of design of experiments (DOE) and optimization techniques, as a powerful quantitative tool to determine the best levels for the parameters and to quantify the significance and interaction of the involved factors, strengthening the analysis and managerial highlights. In some cases, the design of experiments can be especially useful, for the study of factors characterized by nonlinear functions or for the analysis of relationships in complex supply chain systems. To the best of our knowledge, there are few studies that combine DOE and optimization to solve supply chain design problems. Only, Bachlaus et al. [4] had an approximation to this issue. We found few studies of other kinds of supply chain problems solved by the combination of DOE and optimization, most of them dealing with the scheduling of transport routes, like in Raa [5], Hu et al. [6], and Zhang and Xu [7].

In our proposal, once the optimization model has been defined, we propose the use of the design of experiments to analyze the impact of each one of the studied parameters and their interactions, in the objective function. To this aim, an ANOVA analysis is done to analyze the effects of changes, which, unlike a traditional analysis of sensitivity, also takes into account the interactions between variables. Then, the significance of the main factors and interactions are extracted to give robust findings, as well as to find ideal values of the objective function, based on the knowledge of the behavior of the parameters. That is, the analyses fed back each other.

Each factor chosen to be analyzed in this study represents itself a whole area within organization management, but also these factors are indeed interrelated with each other. For example, an increase in supply chain capacity may reduce delivery times, while implying an economic cost, and at the same time, it may yield and increment in the complexity of the network design problem, by a combinatorial increment in the number of feasible solutions. In the case of supply chains, even manufacturing systems can be considered interrelated [8], generating very large and complex systems. Improvements in quality and delivery times require an economic investment, while low quality levels may entail the need to resort to external suppliers. This need for financial resources increases the relevance of the negotiated interest rate. Considering the aforementioned interrelations, one of the objectives of this research is to quantify their influence on the desired result, that is, the maximization of the net benefits. Design of Experiments is a well-known approach for doing these and other similar analyses.

The next subsections briefly discuss some of the most relevant factors for supply chain systems, integrating a review of some related literature. Subsequently, this document is composed of the problem description in Section 2, followed by the proposed mathematical model in Section 3. Afterwards, Section 4 focuses on the case study, where the effectiveness and usefulness of the proposed model are shown, and finally conclusions and future research lines are presented in Section 5.

1.1. Quality and Process Capability Index (Cp and Cpk) in the Supply Chain. In the literature, supply chain management and quality have been approached upon different perspectives, such as product quality and service quality [9–13], reprocessing and reworking in inventory models [14], quality costs [15], quality as a strategy [16–18], selection of suppliers [19], and the integration of capability indexes for the evaluation of products and performance of organizations [20–25].

For considering the quality factor in the supply chain, a well-known approach is specifying it regarding costs of quality (COQ) and cost of poor quality (COPQ) [15, 26]. In this study we will focus on the COPQ, based on the percentage of product that does not meet specifications which is estimated using the process capability index *(Cpk)*, multiplied by the cost related to reprocessing and rework. Although other pertinent costs of poor quality of external or indirect nature may be considered [27], in this case the focus is on the costs derived from products out of specifications, since this is a chronic and important concern in the supply chain under study.

The process capability indexes (*Cp* or *Cpk*) define the capability of a process to meet customer specifications. Equation (1) represents the calculation of *Cp* using the upper specification limit (USL), the lower specification limit (LSL), and the standard deviation (σ). Equation (2a) represents the calculation of the lower *Cpkl* using the mean (μ), the lower specification limit (LSL), and the standard deviation (σ). Equation (2b) represents the calculation of the upper $Cpku$ using the upper specification limit (USL), the mean, and the standard deviation.

$$Cp = \frac{\text{USL} - \text{LSL}}{6\sigma} \tag{1}$$

$$Cpkl = \frac{\mu - \text{LSL}}{3\sigma} \tag{2a}$$

$$Cpku = \frac{\text{USL} - \mu}{3\sigma}. \tag{2b}$$

There is literature considering different approaches for using the indexes of process capability, such as graphs for analysis and comparison of $Cpkl$, $Cpku$, and Cp [28], hypothesis tests for selection of suppliers [29], graphs relating capability index and price comparison [30], fuzzy integration of multiple criteria and attributes [31], simulation with self-correlated data [32], multivariate process capability [33], supplier selection decisions based on stochastic dominance [34], and supplier relationship analysis of manufacturing firms [35].

1.2. Delivery Time and Service Level. Improvements in production quality, reductions in defects and reprocessing, variability decrease, and operations synchronizing are recognized as key elements to achieve on-time delivery of raw material and finished products within the supply chain. The analysis of delivery performance is critical to manage and control the total time in a supply chain, since improvements in delivery times involve economic investment that must be quantified. Research has been carried out for these purposes, in which a time-of-delivery window and graph analysis are integrated to evaluate the performance of the deliveries, incorporating indexes of process capability as key elements in decision-making at the time of the purchase [36]. More recently, Bushuev [37] analyzes and demonstrates strategies for improving delivery performance when a supplier uses an optimally positioned delivery window to minimize the expected penalty costs. In other researches, dynamic mechanisms for early-warning safety are proposed for the quality of the supply chain where they operate according to the disturbance of waiting time [38].

1.3. Interest Rate. For the problem considered in this research, a desired or target quotation for the raw materials and the products through the supply chain is established. If the capacity of the suppliers that provide raw materials for a given price or a smaller one is reached, the supplier's quality performance does not allow accomplishing the contractual commitments, or the delivery standards are not adequate, then it is necessary to search for supply sources at higher costs, which must be financially supported through a loan. The conditions of these loans may vary according to their origin; therefore, it is necessary to consider a reference for the calculation of the amount to be paid on capital. In this paper, an interest rate is used as a benchmark. The interest rate is a representative fee of credit operations between banks, and it serves as a reference for loans to individuals. An infinite number of articles have been published regarding financial decisions and loans in the context of a supply chain. We highlight in this respect the recent work of Zhou et al. [39] who analyze how a capital-constrained retailer can determine their optimal advertising/ordering policy, selecting the best financing mode, according to their initial capital level and the interest rates of the financial services.

2. Problem Statement

The problem studied in this research is described in this section, which is based on the following assumptions:

(1) The use of data to calculate process capacities is regarded under stable process conditions and statistical control.

(2) The processes have a normal distribution behavior, and the individual quality for each process is independent of the others.

(3) The tolerance for the delivery time of raw material or products defined by the customer is called the "delivery time window."

(4) The interest rates are based on historical figures published from 2009 to 2015 by the country's Federal Bank.

The problem is to optimize the supply chain network in a static, single-period scenario, involving decisions of locating plants and distribution centers, supplier selection, quantities to be manufactured, and material flows between suppliers and manufacturers, from manufacturers to distribution centers, and between distribution centers and end customers, for a set of end products and raw materials. The aim is to maximize net benefits of the entire supply chain system, satisfying all end customer demands for each product.

2.1. Use of Capability Indexes in the Computation of Costs. The following paragraphs are aimed at describing and defining some of the main problem parameters, related to supply chain system costs.

The total quality cost is illustrated as CTC integrated by the sum of the poor quality costs of each of the $RRTR$, $RRTF$, and $RRTD$ echelons for suppliers, manufacturers, and distribution centers, respectively. The calculation of the poor quality cost for the case of the suppliers that supply the material to the manufacturers, denominated as $RRTR$, is illustrated below. This same calculation will be made for the other $RRTF$ and $RRTD$ echelons.

We start calculating the upper processing capability index $Cpku$ and the lower processing capability index $Cpkl$ of quality for both ends of the curve, for each of the materials and products that supply each of the suppliers, manufacturers, and distribution centers. Equation (3) represents Cp for the material m sent by the supplier r to the manufacturer f. This calculation is done by taking the mean, the lower specification limit, and the standard deviation. Equation (4a) represents the lower Cpk for the material m sent by the supplier to the manufacturer f. This calculation is done using the mean, the lower specification limit, and the standard deviation. Equation (4b) represents the upper *Cpk* for the material m provided by the supplier to the manufacturer f. This calculation is done by taking the upper specification limit, the mean, and the standard deviation.

$$CpCR_{mrf} = \frac{\mathrm{USL}_{mrf} - \mathrm{LSL}_{mrf}}{6\sigma_{mrf}} \quad (3)$$

$$CpklCR_{mrf} = \frac{\mu_{mrf} - \mathrm{LSL}_{mrf}}{3\sigma_{mrf}} \quad (4a)$$

$$CpkuCR_{mrf} = \frac{\mathrm{USL}_{mrf} - \mu_{mrf}}{3\sigma_{mrf}}. \quad (4b)$$

Calculated *Cpk's* will be used to determine the percentage of nonconforming material or product that does not meet established quality limits (see (5)). This will be done using the resulting probability density function for each concept, which results in the percentage of product that does not meet specifications (% NC), taking into account the lower specification limit and the upper specification limit of the customer (LSL and USL) [24].

$$\%\ \mathrm{NC} = 1 - \Phi\left(\frac{\mathrm{USL} - \mu}{\sigma}\right) + \Phi\left(\frac{\mu - \mathrm{LSL}}{\sigma}\right). \quad (5)$$

Once the percentage of nonconforming products that do not meet specifications is obtained, these are classified into two types: reprocessing and rework [40]. This percentage will be used to calculate the cost of poor quality taking into account the cost of reprocessing and the cost of rework, as well as the reprocessing rate and rework rate for each echelon.

(i) Reprocessing consists of processing a batch or subbatch of materials of unacceptable quality, by repeating the same process steps of a defined stage of production so that its quality can be made acceptable, that is, the repetition of one or more steps of a process during manufacturing after it is known that the product has not met the preset limits.

(ii) Rework consists of processing a batch or subbatch of materials of unacceptable quality by a process other than the one used to produce the material in the original way, to achieve acceptable quality [41], as shown in Figure 2.

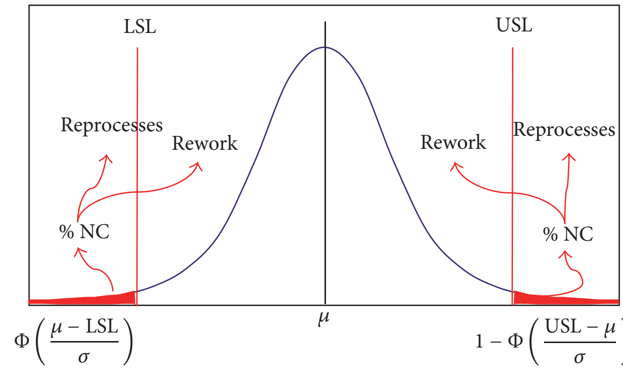


Figure 2: Percentage of nonconforming product for reprocessing and rework.

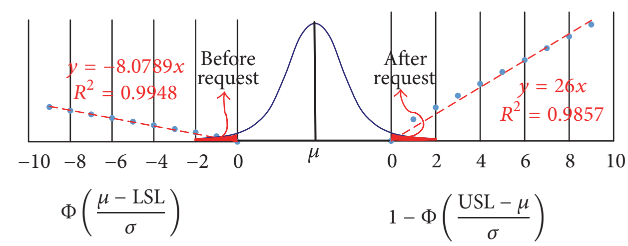


Figure 3: Cost of delivery time in the delivery time window.

For the calculation of the cost occasioned by the delivery time, a similar approach to the one of poor quality is considered. The capability indexes are calculated according to the maximum and minimum allowable delivery time, which acts as a specification limit (Linn, 2006). The mean and standard deviation are derived from the supplier's delivery records according to each echelon in the supply chain. These calculations are based on the concept of delivery time window proposed by Hsu et al. [36], as shown in Figure 3.

Once the indexes of capability for the delivery time have been obtained, the percentage of product that does not comply with the specification is calculated, either because it is delivered after the requested time or because it is delivered before the requested time. The above will be used to fit a simple linear regression according to the days of lag with respect to the target time.

The cost of financing is integrated into the chain based on the manufacturer's price and the distribution center's price. The difference between the actual prices and the target price of the materials or products is considered, and this difference will be multiplied by the quantity sent and by the interest rate.

Once the costs of poor quality, delivery time, and financing have been calculated, the other costs are integrated into the model, consisting of the costs of operating and placing the product in the different facilities. These are the costs of purchasing material, the cost of producing, cost of transportation, and the cost of operating facilities [12, 42, 43]. It is important to mention that all other costs strongly depend on the general quality performance of the processes, especially the operation costs, which can be affected by a high rate of losses in production.

3. Mathematical Formulation

This section presents the indexes, parameters, decision variables, and the entire mathematical model. This is a mixed-integer linear program (MILP), having continuous variables representing the quantity of goods circulating in the supply chain and integer binary variables representing the decisions to open or not a location.

Indexes

m: material

p: product

r: supplier

f: manufacturer

d: distribution center

c: customer

Parameters

Quality Parameters

$RRTR_{mrf}$: total quality cost of material m shipped from the supplier r to manufacturer f

$RRTF_{pfd}$: total quality cost of the product p shipped from the manufacturer f to the distribution center d

$RRTD_{pdc}$: total quality cost of the product p shipped from the distribution center d to the customer c

$CpCR_{mrf}$: quality value obtained from Cp for each supplier r

$CpCF_{pfd}$: quality value obtained from Cp for each manufacturer f

$CpCD_{pdc}$: quality value obtained from Cp for each distribution center d

$CpkCR_{mrf}$: quality value obtained from Cpk for each supplier r

$CpkCF_{pfd}$: quality value obtained from Cpk for each manufacturer f

$CpkCD_{pdc}$: quality value obtained from Cpk for each distribution center d

$CpkuCR_{mrf}$: quality value obtained from high Cpk for each supplier r

$CpkuCF_{pfd}$: quality value obtained from high Cpk for each manufacturer f

$CpkuCD_{pdc}$: quality value obtained from high Cpk for each distribution center d

$CpklCR_{mrf}$: quality value obtained from low Cpk for each supplier r

$CpklCF_{pfd}$: quality value obtained from Cpk low for each manufacturer f

$CpklCD_{pdc}$: quality value obtained from Cpk low for each distribution center d

RR_{mrf}: reprocessing cost of the material m of supplier r to manufacturer f

RTR_{mrf}: reworking cost of the material m of supplier r to manufacturer f

$TRPR_{mrf}$: rate of reprocessing of material m of supplier r to manufacturer f

$TRTR_{mrf}$: rate of rework of material m of supplier r to manufacturer f

RF_{pfd}: reprocessing cost of product p of manufacturer f to the distribution center d

RTF_{pfd}: rework cost of product p of manufacturer f to the distribution center d

$TRPF_{pfd}$: reprocessing rate of product p of manufacturer f to the distribution center d

$TRTF_{pfd}$: reworking rate of product p of manufacturer f to the distribution center d

RD_{pdc}: reprocessing cost of product p of distribution center d to the customer c

RTD_{pdc}: rework cost of product p of distribution center d to the customer c

$TRPD_{pdc}$: reprocessing rate of product p of distribution center d to customer c

$TRTD_{pdc}$: reworking rate of product p of distribution center d to customer c

ΦR_{mrf}: probability density function of the quality characteristic of material m from the supplier r to manufacturer f

ΦF_{pfd}: probability density function of the quality characteristic of product p from the manufacturer f to the distribution center d

ΦD_{pdc}: probability density function of the quality characteristic of product p from the distribution center d to the customer c

Delivery Time Parameters

$CTER_{mrf}$: total cost per out-of-time delivery of material m shipped from supplier r to manufacturer f

$CTEF_{pfd}$: total cost per out-of-time delivery of product p shipped from manufacturer f to the distribution center d

$CTED_{pdc}$: total cost per out-of-time delivery of product p shipped from the distribution center d to the customer c

$TR\mathrm{USL}_{mrf}$: late delivery time limit of material m delivered by supplier r to manufacturer f

$TR\mathrm{LSL}_{mrf}$: earlier delivery time limit of material m provided by supplier r to manufacturer f

$TF\mathrm{USL}_{pfd}$: late delivery time limit of product p shipped by manufacturer f to distribution center d

$TF\mathrm{LSL}_{prd}$: early delivery time limit of product p shipped by manufacturer f to distribution center d

$TD\mathrm{USL}_{pdc}$: late delivery time limit of product p delivered by the distribution center d to customer c

$TD\mathrm{LSL}_{pdc}$: early delivery time limit of product p delivered by the distribution center d to customer c

$TR\mu_{mrf}$: average of delivery time of material m provided by supplier r to manufacturer f

$TR\sigma_{mrf}$: standard deviation of delivery time of material m provided by supplier r to manufacturer f

$TF\mu_{pfd}$: average of delivery time of product p transported from the manufacturer f to the distribution center d

$TF\sigma_{pfd}$: standard deviation of delivery time of product p transported from the manufacturer f to the distribution center d

$TD\mu_{pdc}$: average of delivery time of product p delivered from the distribution center d to customer c

$TD\sigma_{pdc}$: standard deviation of delivery time of product p delivered from the distribution center d to the customer c

$PDTR_{mrf}$: constant of the slope of the equation of the cost of delivering after the limit time for the material m of supplier r to the manufacturer f

$DDTR_{mrf}$: quantity of delivery days after the limit time of material m from supplier r to manufacturer f

$PATR_{mrf}$: constant of the slope of the equation of the daily cost of delivering before the limit time of material m from supplier r to manufacturer f

$DATR_{mrf}$: quantity of delivery days before the limit time of material m from supplier r to manufacturer f

$PDTF_{pfd}$: constant of the slope of the equation of the cost of delivering after the limit time for the product p from manufacturer f to distribution center d

$DDTF_{pfd}$: quantity of delivery days after the limit time of product p of manufacturer f to distribution center d

$PATF_{pfd}$: constant of the slope of the equation of the cost of delivering before the limit time for the product p from manufacturer f to distribution center d

$DATF_{pfd}$: quantity of delivery days before the limit time of product p from the manufacturer f to distribution center d

$PDTD_{pdc}$: constant of the slope of the equation of the cost of delivering after the limit time for the product p from the distribution center d to customer c

$DDTD_{pdc}$: quantity of delivery days after the limit time of product p from the distribution center d to customer c

$PATD_{pdc}$: constant of the slope of the equation of the cost of delivering before the limit time for the product p from the distribution center d to customer c

$DATD_{pdc}$: quantity of delivery days before the limit time of product p from the distribution center d to customer c

$TMDER_{mrf}$: rate of quantity delivered after the limit time of material m from supplier r to manufacturer f

$TMAER_{mrf}$: rate of material provided before the limit time, of material m from supplier r to manufacturer f

$TPDEF_{pfd}$: rate of product delivered after the limit time, of product p from manufacturer f to distribution center d

$TPAEF_{pfd}$: rate of product delivered before the limit time, of product p from manufacturer f to distribution center d

$TPDED_{pdc}$: rate of product delivered after the limit time of product p from distribution center d to customer c

$TPAED_{pdc}$: rate of product delivered before the limit time of product p from distribution center d to customer c

ΦTER_{mrf}: probability density function of the delivery time of material m from the supplier r to manufacturer f

ΦTEF_{pfd}: probability density function of the delivery time of product p from the manufacturer f to distribution center d

ΦTED_{pdc}: probability density function of the delivery time of product p from the distribution center d to customer c

Interest Rate Parameters

CPR_{mrf}: cost of financing for a price higher than the target price of the material m sent from the supplier r to manufacturer f

CPF_{pfd}: cost of financing for a price higher than the target price of product p shipped from the manufacturer f to distribution center d

PR_{mr}: actual price of material m from supplier r

PF_{pf}: actual price of product p from manufacturer f

PD_{pd}: actual price of product p from distribution center d

TR_{mr}: target price of material m of supplier r

TF_{pf}: target price of product p of manufacturer f

FRF_f: interest rate for the manufacturer f

FRD_d: interest rate for the distribution center d

DY_r: cost of starting operations with supplier r

FF_f: cost of starting operations with manufacturer f

DA_d: cost of starting operations of the distribution center d

DOA_f: production capacity for the product p by the manufacturer f

DOV_d: delivery capacity for the product p by the distribution center d

DEM_{pc}: requested quantity of product p by the customer c

BV_{mr}: production capacity of material m by supplier r

MT_{mrf}: cost per unit to send material m from supplier r to manufacturer f

AB_{pfd}: cost per unit to send product p from manufacturer f to distribution center d

YM_{pdc}: cost per unit to send product p from the distribution center d to customer c

PO_{mp}: quantity of material m to produce product p

FAp_f: cost per unit to manufacture product p made by manufacturer f

$COSTMP1_{mrf}$: total cost of purchasing material m to supplier r by manufacturer f

Decision Variables

$YPROV_r$: binary variable of "1" to start operations, or "0" not to start operations for the supplier r

$YFABR_f$: binary variable of "1" to start operations, or "0" not to start operations for the manufacturer f

YCD_d: binary variable of "1" to start operations, or "0" not to start operations for the distribution center d

QR_{mrf}: quantity of material m from supplier r to manufacturer f

QF_{pfd}: quantity of product p from manufacturer f to distribution center d

QD_{pdc}: quantity of product p from the distribution center d to customer c

$VOLMP_{mf}$: volume received of material m to the manufacturer f

$VOLFAB_{pf}$: volume transformed of product p by manufacturer f

Cost Modeling. The cost of poor quality is calculated by taking into account the cost of reprocessing RR and the cost of rework RTR as well as the reprocessing rate $TRPR$ and the rework rate $TRTR$ for each echelon. Here, it is important to mention that the calculation of reprocessing and rework costs is not trivial since, for example, a reworked defective part can be defective again and may not go directly back to the production flow. Equation (6) shows the calculations of rework to be performed, where m represents the raw material, r represents the supplier, and f represents the manufacturer. Here, the quantity of material m of supplier r is multiplied by the percentage of product p below the specification and the amount of product p that is above the specification, which in turn are multiplied by the cost and rate of rework plus reprocessing cost and rate.

$$RRTR = \sum_{m=1}^{M}\sum_{r=1}^{R}\sum_{f=1}^{F}\left\{QR_{mrf}\cdot\left[\left(\left(\Phi R_{mrf}\right)\cdot\left(-3CpklCR_{mrf}\right)\right)+\left(\left(\Phi R_{mrf}\right)\cdot\left(-3\left(2CpCR_{mrf}-CpkuCR_{mrf}\right)\right)\right)\right]\cdot\left(RR_{mrf}\cdot TRPR_{mrf}+RTR_{mrf}\cdot TRTR_{mrf}\right)\right\}. \quad (6)$$

In (7), it is possible to observe the calculation for the cost caused by deviations in the delivery time, which is affected by the days of lag with respect to the target time, as well as the quantity that was delivered out of time and the cost per day delivered out of time. In this first part, QR_{mrf} represents the quantity to be transported of material m by the supplier r to manufacturer f, multiplied by the rate $TMAER_{mrf}$. This outcome is multiplied by the percentage delivered before the due date, which is finally multiplied by the product of the slope constant of the cost equation per day of delivery before the time limit ($PATR_{mrf}$) and the number of days of premature delivery of the material m from the supplier r to the manufacturer f ($DATR_{mrf}$).

$$CTER = \sum_{m=1}^{M}\sum_{r=1}^{R}\sum_{f=1}^{F}\left\{\left[\left(QR_{mrf}\cdot TMDER_{mrf}\right)\left(1-\Phi TER_{mrf}\left(\frac{TRUSL_{mrf}-TR\mu_{mrf}}{TR\sigma_{mrf}}\right)\right)\left(PDTR_{mrf}\cdot DDTR_{mrf}\right)\right]+\left[\left(QR_{mrf}\cdot TMAER_{mrf}\right)\left(\Phi TER_{mrf}\left(\frac{TR\mu_{mrf}-TRLSL_{mrf}}{TR\sigma_{mrf}}\right)\right)\left(PATR_{mrf}\cdot DATR_{mrf}\right)\right]\right\}. \quad (7)$$

The cost of the interest rate (CTP) is integrated into the model in (8) showing the total financing cost in the supply chain, based on the costs of the manufacturer (CPR_{mrf}) and the distribution center (CPF_{pfd}). Equation (9) shows the calculation for each echelon by means of multiplication only resulting from the difference of the real prices ($-PR_{mr}$) and target price (TR_{mr}) of the materials or products according to the case of the echelon that exceeds the target price for which the difference of the real price in relation to the target price will be calculated, and this difference will be multiplied by the amount sent (QR_{mrf}) and by the assigned interest rate. This will be verified in three scenarios (low, average, and high rate) to determine the cost of the financing rate (FRF_f), based on the value of the interest rate, calculated from the last five historical years recorded by the financial institution corresponding to the country.

$$CTP = CPR_{mrf} + CPF_{pfd} \quad (8)$$

$$CPR_{mrf} = \sum_{m=1}^{M}\sum_{r=1}^{R}\sum_{f=1}^{F}\left\{\max\left[0,\left(-PR_{mr}+TR_{mr}\right)\right]\cdot QR_{mrf}\cdot FRF_f\right\}. \quad (9)$$

The cost of purchasing material is obtained using the amount to be purchased for the actual price (*COSTMP*1) expressed in (10). The cost of producing *(PRODUCE)* in (11) is calculated for each product p of each manufacturer f by multiplying the cost of manufacturing by the volume manufactured. The cost of transportation *(TRANSPORT)* in (12) is the cost of sending the material or product to its requested destination along each of the echelons of the supply chain. The cost of operating *(COSTOPERATE)* in (13) of each of the echelons that make up the supply chain is represented by the multiplication of the cost of operating and its binary variable.

$$COSTMP1_{mrf} = \sum_{m=1}^{M}\sum_{r=1}^{R}\left(QR_{mrf}\cdot PR_{mr}\right) \tag{10}$$

$$PRODUCE = \sum_{p=1}^{P}\sum_{f=1}^{F}\left(FA_{pf}\cdot VOLFAB_{pf}\right) \tag{11}$$

$$\begin{aligned} TRANSPORT = {} & \sum_{m=1}^{M}\sum_{r=1}^{R}\sum_{f=1}^{F}\left(MT_{mrf}\cdot QR_{mrf}\right) \\ & + \sum_{p=1}^{P}\sum_{f=1}^{F}\sum_{d=1}^{D}\left(AB_{pfd}\cdot QF_{pfd}\right) \\ & + \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{c=1}^{C}\left(YM_{pdc}\cdot QD_{pdc}\right) \end{aligned} \tag{12}$$

$$\begin{aligned} COSTOPERATE = {} & \sum_{r=1}^{R}\left(DY_{r}\cdot YPROV_{r}\right) + \sum_{f=1}^{F}\left(FF_{f}\right. \\ & \left.\cdot YFABR_{f}\right) + \sum_{d=1}^{D}\left(DA_{d}\cdot YCD_{d}\right). \end{aligned} \tag{13}$$

Mixed-Integer Linear Program

$$\text{Objective Function: Maximize Profitability} \tag{14}$$

$$\text{Profitability} = \text{Earnings} - \text{Expenses} \tag{15a}$$

$$\text{Earnings} = \sum_{p=1}^{P}\sum_{d=1}^{D}\left(QD_{pdc}\cdot PD_{pd}\right) \tag{15b}$$

$$\text{Expenses} = CTC + CTT + CTP + COSTMP1 + PRODUCE + TRANSPORT + COSTOPERATE \tag{15c}$$

$$CTC = RRTR_{mrf} + RRTF_{pfd} + RRTD_{pdc} \tag{16}$$

$$CpCR_{mrf} = \frac{\mathrm{USL}_{mrf} - \mathrm{LSL}_{mrf}}{6\sigma_{mrf}} \tag{17}$$

$$CpkuCR_{mrf} = \frac{\mathrm{USL}_{mrf} - \mu_{mrf}}{3\sigma_{mrf}} \tag{18}$$

$$CpklCR_{mrf} = \frac{\mu_{mrf} - \mathrm{LSL}_{mrf}}{3\sigma_{mrf}} \tag{19}$$

$$CpkCR_{mrf} = \min\left\{CpkuCR_{mrf}, CpklCR_{mrf}\right\} \tag{20}$$

$$RRTR_{mrf} = \sum_{m=1}^{M}\sum_{r=1}^{R}\sum_{f=1}^{F}\left\{QR_{mrf}\cdot\left[\left(\Phi R_{mrf}\left(-3CpklCR_{mrf}\right)\right) + \left(\Phi R_{mrf}\left(-3\left(2CpCR_{mrf} - CpkuCR_{mrf}\right)\right)\right)\right]\cdot\left[\left(RR_{mrf}\cdot TRPR_{mrf}\right) + \left(RTR_{mrf}\cdot TRTR_{mrf}\right)\right]\right\} \tag{21}$$

$$CpCF_{pfd} = \frac{\mathrm{USL}_{pfd} - \mathrm{LSL}_{pfd}}{6\sigma_{pfd}} \tag{22}$$

$$CpkuCF_{pfd} = \frac{\mathrm{USL}_{pfd} - \mu_{pfd}}{3\sigma_{pfd}} \tag{23}$$

$$CpklCF_{pfd} = \frac{\mu_{pfd} - \mathrm{LSL}_{pfd}}{3\sigma_{pfd}} \tag{24}$$

$$CpkCF_{pfd} = \min\left\{CpkuCF_{pfd}, CpklCF_{pfd}\right\} \tag{25}$$

$$RRTF_{pfd} = \sum_{p=1}^{P}\sum_{f=1}^{F}\sum_{d=1}^{D}\left\{QF_{pfd}\cdot\left[\left(\Phi F_{pfd}\left(-3CpklCF_{pfd}\right)\right) + \left(\Phi F_{pfd}\left(-3\left(2CpCF_{pfd} - CpkuCF_{pfd}\right)\right)\right)\right]\cdot\left[\left(RF_{pfd}\cdot TRPF_{pfd}\right) + \left(RTF_{pfd}\cdot TRTF_{pfd}\right)\right]\right\} \tag{26}$$

$$CpCD_{pdc} = \frac{\text{USL}_{pdc} - \text{LSL}_{pdc}}{6\sigma_{pdc}} \tag{27}$$

$$CpkuCD_{pdc} = \frac{\text{USL}_{pdc} - \mu_{pdc}}{3\sigma_{pdc}} \tag{28}$$

$$CpklCD_{pdc} = \frac{\mu_{pdc} - \text{LSL}_{pdc}}{3\sigma_{pdc}} \tag{29}$$

$$CpkCD_{pdc} = \min\left\{CpkuCR_{pdc}, CpklCR_{pdc}\right\} \tag{30}$$

$$RRTD_{pdc} = \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{c=1}^{C}\left\{QD_{pdc}\cdot\left[\left(\Phi D_{pdc}\left(-3CpklCD_{pdc}\right)\right) + \left(\Phi D_{pdc}\left(-3\left(2CpCD_{pdc} - CpkuCD_{pdc}\right)\right)\right)\right]\cdot\left[\left(RD_{pdc}\cdot TRPD_{pdc}\right) + \left(RTD_{pdc}\cdot TRTD_{pdc}\right)\right]\right\} \tag{31}$$

$$CTC = RRTR_{mrf} + RRTF_{pfd} + RRTD_{pdc} \tag{32}$$

$$CTER_{mrf} = \sum_{m=1}^{M}\sum_{r=1}^{R}\sum_{f=1}^{F}\left\{\left[\left(QR_{mrf}\cdot TMDER_{mrf}\right)\left(1 - \Phi TER_{mrf}\left(\frac{TR\text{USL}_{mrf} - TR\mu_{mrf}}{TR\sigma_{mrf}}\right)\right)\left(PDTR_{mrf}\cdot DDTR_{mrf}\right)\right] + \left[\left(QR_{mrf}\cdot TMAER_{mrf}\right)\left(\Phi TER_{mrf}\left(\frac{TR\mu_{mrf} - TR\text{LSL}_{mrf}}{TR\sigma_{mrf}}\right)\right)\left(PATR_{mrf}\cdot DATR_{mrf}\right)\right]\right\} \tag{33}$$

$$CTEF_{pfd} = \sum_{p=1}^{P}\sum_{f=1}^{F}\sum_{d=1}^{D}\left\{\left[\left(QF_{pfd}\cdot TPDEF_{pfd}\right)\left(1 - \Phi TEF_{pfd}\left(\frac{TF\text{USL}_{pfd} - TF\mu_{pfd}}{TF\sigma_{pfd}}\right)\right)\left(PDTF_{pfd}\cdot DDTF_{pfd}\right)\right] + \left[\left(QF_{pfd}\cdot TPAEF_{pfd}\right)\left(\Phi TEF_{pfd}\left(\frac{TF\mu_{pfd} - TF\text{LSL}_{pfd}}{TF\sigma_{pfd}}\right)\right)\left(PATF_{pfd}\cdot DATF_{pfd}\right)\right]\right\} \tag{34}$$

$$CTED_{pdc} = \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{c=1}^{C}\left\{\left[\left(QD_{pdc}\cdot TPDED_{pdc}\right)\left(1 - \Phi TED_{pdc}\left(\frac{TD\text{USL}_{pdc} - TD\mu_{pdc}}{TD\sigma_{pdc}}\right)\right)\left(PDTD_{pdc}\cdot DDTD_{pdc}\right)\right] + \left[\left(QD_{pdc}\cdot TPAED_{pdc}\right)\left(\Phi TED_{pdc}\left(\frac{TD\mu_{pdc} - TD\text{LSL}_{pdc}}{TD\sigma_{pdc}}\right)\right)\left(PATD_{pdc}\cdot DATD_{pdc}\right)\right]\right\} \tag{35}$$

$$CTP = CPR_{mrf} + CPF_{pfd} \tag{36}$$

$$CPR_{mrf} = \sum_{m=1}^{M}\sum_{r=1}^{R}\sum_{f=1}^{F}\left\{\max\left[0, \left(-PR_{mr} + TR_{mr}\right)\cdot QR_{mrf}\cdot FRF_f\right]\right\} \tag{37}$$

$$CPF_{pfd} = \sum_{p=1}^{P}\sum_{f=1}^{F}\sum_{d=1}^{D}\left\{\max\left[0, \left(-PF_{pf} + TF_{pf}\right)\cdot QF_{pfd}\cdot FRD_d\right]\right\} \tag{38}$$

$$COSTMP1_{mrf} = \sum_{m=1}^{M}\sum_{r=1}^{R}\left(QR_{mrf}\cdot PR_{mr}\right) \tag{39}$$

$$PRODUCE = \sum_{p=1}^{P}\sum_{f=1}^{F}\left(FA_{pf}\cdot VOLFAB_{pf}\right) \tag{40}$$

$$TRANSPORT = \sum_{m=1}^{M}\sum_{r=1}^{R}\sum_{f=1}^{F}\left(MT_{mrf}\cdot QR_{mrf}\right) + \sum_{p=1}^{P}\sum_{f=1}^{F}\sum_{d=1}^{D}\left(AB_{pfd}\cdot QF_{pfd}\right) + \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{c=1}^{C}\left(YM_{pdc}\cdot QD_{pdc}\right) \tag{41}$$

$$COSTOPERATE = \sum_{r=1}^{R}\left(DY_r\cdot YPROV_r\right) + \sum_{f=1}^{F}\left(FF_f\cdot YFABR_f\right) + \sum_{d=1}^{D}\left(DA_d\cdot YCD_d\right) \tag{42}$$

$$\text{S.t.}\quad \sum_{d=1}^{D} QD_{pdc} \geq DEM_{pc} \quad \forall p, c \tag{43}$$

$$\sum_{d=1}^{D} QF_{pfd} \leq VOLFAB_{pf} \quad \forall p, f \tag{44}$$

$$\sum_{p=1}^{P} VOLFAB_{pf} \leq DOA_f\cdot YFABR_f \quad \forall f \tag{45}$$

$$\sum_{p=1}^{P}\sum_{c=1}^{C} QD_{pdc} \leq DOV_d\cdot YCD_d \quad \forall d \tag{46}$$

$$\sum_{p=1}^{P} VOLFAB_{fp}\cdot PO_{mp} \leq \sum_{r=1}^{R} QR_{mrf} \quad \forall m, f \tag{47}$$

$$VOLMP_{mf} = \sum_{p=1}^{P} VOLFAB_{fp} \cdot PO_{mp} \quad \forall m, f \tag{48}$$

$$VOLMP_{mf} = \sum_{r=1}^{R} QR_{mrf} \quad \forall m, f \tag{49}$$

$$\sum_{f=1}^{F} QR_{mrf} \leq BV_{mr} \cdot YPROV_{r} \quad \forall m, r \tag{50}$$

$$\sum_{p=1}^{P} \sum_{f=1}^{F} QF_{pfd} \leq DOV_{d} \cdot YCD_{d} \quad \forall d \tag{51}$$

$$\sum_{f=1}^{F} QF_{pfd} = \sum_{c=1}^{C} QD_{pdc} \quad \forall p, d. \tag{52}$$

The instance presented in this paper is not designed to explicitly reflect a trade-off between different kinds of costs. However, it is expected that the optimization model helps to compensate costs with others when obtaining the optimal solution. The objective is to maximize the profit, in (14), and is defined in (15a) as the difference between Earnings and Expenses. Equation (15b) is obtained by multiplying the quantity of product sold (QDpdc) by the actual price of the product (PDpd). Expenses are defined in (15c), integrated by the sum of the total costs of CTC, CTT, COSTMP1, PRODUCE, TRANSPORT, and COSTOPERATE. The total quality cost (CTC) is defined in (16) and it is comprised of the sum of the poor quality costs (reprocessing and rework) of $RRTR_{mrf}$, $RRTF_{pfd}$, and $RRTD_{pdc}$. Equation (17) determines the process capability index (*Cp*) for each supplier. Equation (19) calculates the low *Cpk* of the supplied material. Equation (20) determines the actual process capability index (*Cpk*) for each supplier. Equation (21) is composed of the total cost of reprocessing and rework of each raw material m that each supplier r supplies to each manufacturer f (*RRTR*). Equation (22) determines the process capability index (*Cp*) for each manufacturer. Equation (23) calculates the upper *Cpku* of the manufacturer's product. Equation (24) calculates the lower *Cpkl*. Equation (26) refers to the total cost of reprocessing and rework for each product p by each manufacturer f. Equation (27) determines the process capability index (*Cp*) for each distribution center. Equation (28) calculates the upper *Cpku* of the products of the distribution center. Equation (29) calculates the lower *Cpkl* of the products of the distribution center. Equation (30) determines the actual process capability index (*Cpk*) for each distribution center. Equation (31) is composed of the total cost of reprocessing and reworking of each product p that is distributed by the distribution center d and that is supplied to each customer c ($RRTD_{pdc}$). Equation (32) defines the total cost of delivery time (*CTT*) and it is comprised of the sum of the costs of $CTER_{mrf}$, $CTEF_{pfd}$, and $CTED_{pdc}$.

Equation (33) is composed of the total cost of deliveries before the permissible time requested and after the allowable time requested, for each raw material m which each supplier r supplies to each manufacturer f ($CTER_{mrf}$). This cost is taking into account the quantity multiplied by the historical rate of deliveries after the requested time, multiplied by the late arrival rate. Equation (34) is composed of the total cost of deliveries before the requested allowable time and after the permissible time of each product p that is produced by each manufacturer f and distributed by each distribution center d ($CTEF_{pfd}$) taking into account the quantity multiplied by the historical delivery rate after the requested time, multiplied by the late arrival rate. Equation (35) is composed of the total cost of deliveries before the allowable time requested and after the allowable time requested for each product p that each distribution center d supplies to each customer c ($CETD_{pdc}$). This cost is taking into account the quantity multiplied by the historical rate of deliveries after the requested time, multiplied by the late arrival rate. Equation (36) is composed of the total cost of financing (*CTP*) of manufacturers and distribution centers due to the difference of real prices and target prices (CPR_{mrf} and CPF_{pfd}). Equation (37) is composed of the financing cost (CPR_{mrf}) for each manufacturer f due to the difference of the actual price and the target price of each raw material m which each supplier r supplies, multiplied by the quantity and rate of the loan cost corresponding to each manufacturer f for the amount requested. Equation (38) is composed of the cost of financing (CPF_{pfd}) for each distribution center d due to the difference of the actual price and the target price of each product p that each manufacturer f supplies, multiplied by the quantity and rate of the cost of loan corresponding to each distribution center d. Equation (39) defines the costs of buying the raw material m of each supplier r (*COSTMP*1). Equation (40) specifies the total cost of producing the products p by the manufacturer f *(PRODUCE)*. Equation (41) represents the total costs of transportation from the supplier to the manufacturer, from the manufacturer to the distribution center, and from the distribution center to the customer, for each material m and each product p *(TRANSPORT)*. Finally, (42) defines the total cost of operating provider, manufacturer, and distribution center with binary variables *(COST OPERATE)*.

Constraints are defined by the following equations. Equation (43) ensures that the customer's demand is fulfilled.

Equation (44) ensures that the quantity shipped per manufacturer based on the volume is respected. Equation (45) defines that the amount produced is less than the plant capacity. Equation (46) ensures that the quantity of the distribution center is less than that of those activated, using a binary variable to operate the warehouse. Equation (47) ensures that the quantity of material is less than the supplier capacity. Equation (48) converts volume of material to product. Equation (49) ensures that the amount of material is less than the quantity to be sent by the supplier. Equation (50) ensures that the quantity of material sent to the manufacturer is less than the available capacity of each supplier. Equation (51) defines a binary variable to ensure that the manufacturer operates taking into account capacity. Equation (52) ensures that the manufacturer's shipped quantity must be equal to the amount sent from the distribution center to the customer. Here, it is necessary to remember that the model is a single period, which will be appropriate to the planning interval required by the case.

4. Case Study

The supply chain analyzed in the paper consists of four echelons, with 40 suppliers (r) supplying 30 materials (m) to 30 manufacturers (f), which fabricate and supply 20 end products (p) to 30 distribution centers (d), which send the end products to each of 40 customers (c) to meet their demands (DEM_{pc}).

We make changes in the values of capabilities, quality standards, delivery times, and interbank interest rate, each in three levels to be compared. The values of these parameters are generated randomly, following a normal distribution, with several instances according to the design of experiment that will be explained later.

Capacities were considered as follows: high capacity taking 55% above total demand, average capacity taking 35% above total demand, and, finally, a low capacity taking 25% above total demand. This procedure is performed for each supply chain echelon, that is, suppliers (BV_{mr}), manufacturers (DOA_f), and distribution centers (DOV_d). The supply chain must meet customer demand (DEM_{pc}).

For the quality factor, three levels are considered: high quality, medium quality, and low quality. The percentages of defects are determined according to the risks involved in each type of operation at each echelon, where the transformation stage yields higher portions of defects. Thus, the high quality considers a defect rate for suppliers $TDEFPV_{mrf}$ ranging from 0.00 to 0.03, for manufacturers $TDEFF_{pfd}$ ranging from 0.00 to 0.05, and for distribution centers $TDEFW_{pdc}$ ranging from 0.00 to 0.04. The average quality considers a defect rate for suppliers $TDEFPV_{mrf}$ that ranges from 0.04 to 0.08, for manufacturers $TDEFF_{pfd}$ ranging from 0.06 to 0.11, and for distribution centers $TDEFW_{pdc}$ ranging from 0.05 to 0.09. Low quality considers a defect rate for suppliers $TDEFPV_{mrf}$ ranging from 0.09 to 0.14, for manufacturers $TDEFF_{pfd}$ ranging from 0.12 to 0.20, and for distribution centers $TDEFW_{pdc}$ ranging from 0.10 to 0.16 as the minimum value.

For delivery time, different transport alternatives are considered, yielding three delivery times scenarios (low, medium, and high) for each of the supply chain echelons (manufacturer, distribution center, and customer):

(1) Low delivery time: if it is after the time of the requested date, this will be between 0 and 4 days, and if it is before the time of the requested date, this will be between 0 and 4 days.

(2) Average delivery time: if it is after the time of the requested date, this will be between 5 and 15 days, and if it is before the time of the requested date, this will be between 5 and 15 days.

(3) High delivery time: if it is after the time of the requested date, this will be between 16 and 30 days, and if it is before the time of the requested date, this will be between 16 and 30 days.

Finally, for determining the interest rate, three scenarios were considered taking into account the maximum, average, and minimum values recorded according to the periodicity in terms of 28, 91, and 182 days, issued by the country's Federal Bank, which reflect the conditions of the money market in national currency. The three calculated, maximum, average, and minimum, scenarios were used for each of two supply chain echelons (i.e., manufacturer and distribution center) as follows:

(1) Low interest rate, with a value of 3.3 percent, which will apply for those prices above the target value

(2) Average interest rate, with a value of 6 percent, which will be used for those prices above the target value

(3) High interest rate, with a value of 8.7 percent, which will apply for those prices above the target value.

4.1. Solving Procedure. In order to evaluate the impact of the different levels of capacity, quality, delivery time, and interest rate, a fractional-factorial (2^{k-p}) experiment was performed where the following factors were considered: capacity (high, low), quality (high, low), delivery time (high, low), and interest rate (high, low). This results in a 2^{4-1} design, including central points for each of the concepts to explore a possible curvature in the model. Five instances were generated for each of the high and low combinations. Because of the fractional design, this accounts for 40 instances. Fifteen additional instances were generated for the central points included in the design, giving a total of 55 experimental runs.

The proposed model was solved for each instance of the case study using the GAMS-CPLEX software, on an Intel Core 3 processor, 3.0 GB RAM, 2.27 GHz PC. The problem has 82,068 total variables, with 18,100 binary variables. It took between 17 and 25 min to solve each instance, giving a total of 982 minutes to obtain optimal solutions for all instances.

4.2. Results. Table 1 shows the average results of the nine scenarios of the design of fractional-factorial experiment 2^{4-1}, with five central points and with five replicates, in which the calculated profits as well as the total cost and subcosts

Table 1: Summary of costs varying capacity, quality, delivery time, and interest rate.

Capacity	Low	High	Low	High	Low	High	Low	High	Medium
Quality	Low	Low	High	High	Low	Low	High	High	Medium
Delivery time	Low	Low	Low	Low	High	High	High	High	Medium
Interest rate	Low	High	High	Low	High	Low	Low	High	Medium
Profit	$1,360,043.06	$1,339,641.58	$1,938,024.37	$1,968,573.25	$1,056,599.59	$1,062,040.54	$1,690,604.70	$1,718,832.69	$1,509,100.96
Total cost	$2,018,956.94	$2,039,358.42	$1,440,975.63	$1,410,426.75	$2,322,400.41	$2,316,959.46	$1,688,395.30	$1,660,167.31	$1,869,899.04
Quality	$647,879.86	$654,540.73	$62,696.05	$57,216.61	$690,396.33	$699,020.20	$84,562.67	$81,746.51	$352,695.05
Delivery time	$20,584.56	$19,327.68	$16,054.17	$14,683.14	$264,412.27	$244,240.99	$254,161.18	$222,891.04	$154,772.51
Raw material	$201,599.51	$204,765.54	$204,376.27	$200,467.45	$202,948.60	$205,726.42	$200,148.33	$203,940.97	$203,482.32
Production	$178,788.40	$181,096.20	$177,191.20	$175,918.60	$182,851.60	$184,320.40	$181,272.20	$181,497.00	$180,978.53
Transportation	$832,004.20	$850,951.80	$842,811.00	$835,318.00	$840,620.80	$848,430.20	$827,294.80	$840,946.40	$840,930.60
Operation	$136,256.00	$126,928.60	$136,191.60	$125,320.40	$138,975.80	$133,240.80	$138,920.20	$127,206.80	$135,125.47
Interest rate	$1,844.40	$1,747.87	$1,655.34	$1,502.55	$2,195.02	$1,980.45	$2,035.92	$1,938.59	$1,914.56

Table 2: Analysis of variance for profit of each scenario.

Source	Sum of squares	df	Mean square	F test	P value
A: capacity	1.19992E9	1	1.19992E9	0.63	0.4313
B: quality	3.8991E12	1	3.8991E12	2047.87	0.0000
C: delivery time	7.26578E11	1	7.26578E11	381.61	0.0000
D: financing	4.95733E8	1	4.95733E8	0.26	0.6123
AB + CD	3.39825E9	1	3.39825E9	1.78	0.1880
AC + BD	3.4579E8	1	3.4579E8	0.18	0.6719
AD + BC	4.39786E9	1	4.39786E9	2.31	0.1353
Total error	7.7601E10	47	1.90398E9		
Total (corr.)	4.725E12	54			

R-squared = 98.1061 percent; R-squared (adjusted by d.f.) = 97.824 percent; standard error of est. = 43634.6; average absolute error = 31174.2; Durbin-Watson st. = 1.68847 ($P = 0.1647$); residual autocorrelation of Lag 1 = 0.149145.

Table 3: Analysis of variance for profit (adjusted model).

Source	Sum of squares	df	Mean square	F test	P value
B: quality	3.8991E12	1	3.8991E12	2041.32	0.0000
C: delivery time	7.26578E11	1	7.26578E11	380.39	0.0000
Total error	9.93244E10	52	1.91009E9		
Total (corr.)	4.725E12	54			

R-squared = 97.8979 percent; R-squared (adjusted by d.f.) = 97.817 percent; standard error of est. = 43704.5; average absolute error = 35708.6; Durbin-Watson st. = 1.72701 ($P = 0.1321$); residual autocorrelation of Lag 1 = 0.13133.

Table 4: ANOVA for profit by scenario.

Source	Sum of squares	df	Mean square	F test	P value
Between groups	4.63616E12	8	5.7952E11	300.06	0.0000
Within groups	8.88411E10	46	1.93133E9		
Total (corr.)	4.725E12	54			

are expressed. The quality costs, delivery time costs, costs of raw material, costs of production, costs of transport, costs of operation, and cost of financing due to the interest rate are included, where the higher profit is fulfilled with a high capacity, high quality, low delivery time, and low interest rate.

The results of the Analysis of Variance (ANOVA) are shown in Table 2, where the significance of the main factors and double interactions can be observed, obtained with an adjusted R^2 of 98.3577 percent. Higher interactions cannot be scrutinized because of the fractional nature of the design. However, the most significant factors are the main factors: quality and delivery time. These results are confirmed visually in Figure 4.

The model is adjusted according to the significance, resulting in the main factors of the model shown in Table 3, with an adjusted R^2 of 97.817. In Figure 5, the adjusted Pareto chart for the significant effects is shown.

A Simple ANOVA was carried out to evaluate the contribution and variability of each one of the costs for each scenario within the fractional-factorial design, which are shown in Table 4. It can be observed that there are significant differences for each one of the nine scenarios.

Thus, in Figure 6, it can be observed that the high capacity with the high quality (CP.H-C.H) is the group of scenarios with the best profit. The high quality with low capacity (CP.L-C.H) is the second cheapest. These are closely followed by the combination of average capacity with average quality (CP.M-C.M). Figure 7 shows the graph of averages of each scenario.

It can be observed that the highest profit is obtained with high capacity, high quality, low delivery time, and low financing (CP.H-C.H-T.L-F.L). However, the LSD test shows that there is no significant difference in the profit with low capacity, high quality, low delivery time, and high financing (CP.L-C.H-T.L-F.H), as can be seen in Table 5. Figure 7 shows the mean chart of each scenario.

Subsequently, an analysis in terms of costs is performed. These results are shown in Table 6, where it can be observed that there is a significant difference between the costs that affect the profit. In Figure 8, box-and-whisker plot of costs shows the variability of quality costs according to their levels.

A difference between the levels of quality and the dispersion of their data can be seen in Table 7. Also there, it can be observed that delivery time presents a dispersion in their data.

Table 8 presents the percentage of each cost related to the total cost, where transportation cost is the highest, followed by the quality cost and the cost of raw material acquisition. The behavior of profit and costs in an aggregated way is observed in Figure 9.

Table 5: Multiple ranges testing for scenario profit.

(a) method: 95.0 percent LSD

Level	Cases	Mean	Homogeneous groups
CP.L-C.L-T.H-F.H	5	1.0566E6	X
CP.H-C.L-T.H-F.L	5	1.06204E6	X
CP.H-C.L-T.L-F.H	5	1.33964E6	X
CP.L-C.L-T.L-F.L	5	1.36004E6	X
CP.M-C.M-T.M-F.M	15	1.5091E6	X
CP.L-C.H-T.H-F.L	5	1.6906E6	X
CP.H-C.H-T.H-F.H	5	1.71883E6	X
CP.L-C.H-T.L-F.H	5	1.93802E6	X
CP.H-C.H-T.L-F.L	5	1.96857E6	X

(b)

Contrast	Sig.	Difference	+/− limits
CP.H-C.H-T.H-F.H, CP.H-C.H-T.L-F.L	*	−249741	55947.4
CP.H-C.H-T.H-F.H, CP.H-C.L-T.H-F.L	*	656792	55947.4
CP.H-C.H-T.H-F.H, CP.H-C.L-T.L-F.H	*	379191	55947.4
CP.H-C.H-T.H-F.H, CP.L-C.H-T.H-F.L		28228.0	55947.4
CP.H-C.H-T.H-F.H, CP.L-C.H-T.L-F.H	*	−219192	55947.4
CP.H-C.H-T.H-F.H, CP.L-C.L-T.H-F.H	*	662233	55947.4
CP.H-C.H-T.H-F.H, CP.L-C.L-T.L-F.L	*	358790	55947.4
CP.H-C.H-T.H-F.H, CP.M-C.M-T.M-F.M	*	209732	45680.9
CP.H-C.H-T.L-F.L, CP.H-C.L-T.H-F.L	*	906533	55947.4
CP.H-C.H-T.L-F.L, CP.H-C.L-T.L-F.H	*	628932	55947.4
CP.H-C.H-T.L-F.L, CP.L-C.H-T.H-F.L	*	277969	55947.4
CP.H-C.H-T.L-F.L, CP.L-C.H-T.L-F.H		30548.9	55947.4
CP.H-C.H-T.L-F.L, CP.L-C.L-T.H-F.H	*	911974	55947.4
CP.H-C.H-T.L-F.L, CP.L-C.L-T.L-F.L	*	608530	55947.4
CP.H-C.H-T.L-F.L, CP.M-C.M-T.M-F.M	*	459472	45680.9
CP.H-C.L-T.H-F.L, CP.H-C.L-T.L-F.H	*	−277601	55947.4
CP.H-C.L-T.H-F.L, CP.L-C.H-T.H-F.L	*	−628564	55947.4
CP.H-C.L-T.H-F.L, CP.L-C.H-T.L-F.H	*	−875984	55947.4
CP.H-C.L-T.H-F.L, CP.L-C.L-T.H-F.H		5440.96	55947.4
CP.H-C.L-T.H-F.L, CP.L-C.L-T.L-F.L	*	−298003	55947.4
CP.H-C.L-T.H-F.L, CP.M-C.M-T.M-F.M	*	−447060	45680.9
CP.H-C.L-T.L-F.H, CP.L-C.H-T.H-F.L	*	−350963	55947.4
CP.H-C.L-T.L-F.H, CP.L-C.H-T.L-F.H	*	−598383	55947.4
CP.H-C.L-T.L-F.H, CP.L-C.L-T.H-F.H	*	283042	55947.4
CP.H-C.L-T.L-F.H, CP.L-C.L-T.L-F.L		−20401.5	55947.4
CP.H-C.L-T.L-F.H, CP.M-C.M-T.M-F.M	*	−169459	45680.9
CP.L-C.H-T.H-F.L, CP.L-C.H-T.L-F.H	*	−247420	55947.4
CP.L-C.H-T.H-F.L, CP.L-C.L-T.H-F.H	*	634005	55947.4
CP.L-C.H-T.H-F.L, CP.L-C.L-T.L-F.L	*	330562	55947.4
CP.L-C.H-T.H-F.L, CP.M-C.M-T.M-F.M	*	181504	45680.9
CP.L-C.H-T.L-F.H, CP.L-C.L-T.H-F.H	*	881425	55947.4
CP.L-C.H-T.L-F.H, CP.L-C.L-T.L-F.L	*	577981	55947.4
CP.L-C.H-T.L-F.H, CP.M-C.M-T.M-F.M	*	428923	45680.9
CP.L-C.L-T.H-F.H, CP.L-C.L-T.L-F.L	*	−303443	55947.4
CP.L-C.L-T.H-F.H, CP.M-C.M-T.M-F.M	*	−452501	45680.9
CP.L-C.L-T.L-F.L, CP.M-C.M-T.M-F.M	*	−149058	45680.9

* indicates a significative difference.

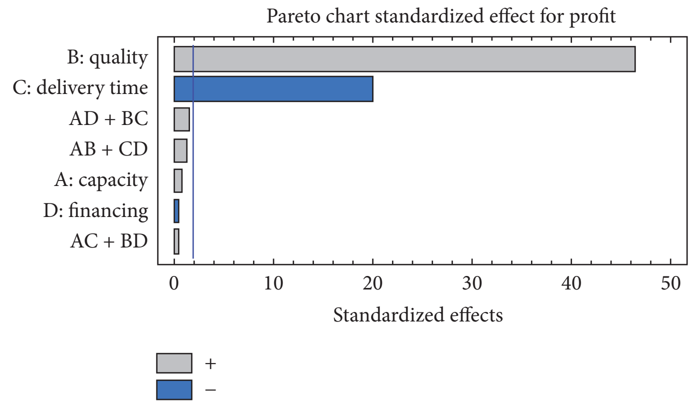


Figure 4: Standardized Pareto for the profit of factors.

Table 6: ANOVA cost per concept.

Source	Sum of squares	df	Mean square	F test	P value
Between groups	2.50075E13	6	4.16791E12	375.18	0.0000
Within groups	4.19929E12	378	1.11092E10		
Total (corr.)	2.92067E13	384			

For Figures 10–17, the different combinations of factors are indicated in the x-axis (I.R. for interest rate, D.T. for delivery time, Q. for quality, and Cap. for capacity), and in the y-axis the disaggregated costs of quality, raw materials, production, transportation, operation, and financial are presented. Figure 10 shows the behavior of the profit for each scenario. Figure 11 shows the total costs, where it is observed how the high quality deeply reduces the total costs.

Figure 12 shows the behavior of the quality cost, which is the second highest of all costs. This figure also shows how, depending on the quality levels, these can significantly influence the profit. Figure 13 shows the costs of raw materials, where it is considered the third most important cost and one of the most stable.

Figure 14 shows the costs of production, which contribute between 7.9% and 12.5% of the costs. Figure 15 shows the behavior of transportation costs, which are the highest, ranging from 41.2% to 59.2% of total costs.

The operating costs are expressed in Figure 16 where they demonstrate being the lowest and the most stable since the operation of the plants is relatively constant. Finally, Figure 17 shows the lowest costs, which for the current rates do not impact the profit in an important way.

In Table 9, the number of facilities used in each echelon is presented for each scenario. Because of the differences in instances in each scenario, the numbers vary, such that only the minimum and maximum are presented for the group of instances of each scenario.

4.3. Findings and Managerial Implications

(i) In the studied case, the highest profit is fulfilled working with a high capacity, high quality, low delivery time, and low interest rate ($1,968,573).

(ii) One of the effects of high capacity is that the number of facilities to operate can be reduced, having a better impact in profits due to a reduction in operating cost. However, an instance with high capacity may be harder to be solved since the number of potential combinations to locate facilities is larger.

(iii) As observed in the results (Table 9), capacity achieves the desired effect reducing the number of distribution centers needed to meet the demand. However, the increase in capacity does not affect the number of suppliers and plants. One explanation for this is that the full set of facilities is needed to be able to transform a large number of raw materials. Then, the supply chain is denser in interactions in the upstream echelons, and the density is reduced downstream, when the number of products is reduced, allowing a reduction in the number of distribution centers needed.

(iv) As expected, high quality impacts profit positively because a lower number of nonconforming products are generated. This not only reduces the costs of reprocessing and rework, but reduces the excess of material that must be considered to meet the demand and that must be purchased taking money from debt (interest rate).

(v) The previous insights agree with common sense, due to the double effect of having more capacity. If we have high capacity, the utility from sales is high too, and at the same time, fewer open facilities are needed. Nevertheless, using low capacity and high financing can give similar results in profit.

(vi) The difference observed between a high and a low quality level is not minor, since the quality has strong

Table 7: Testing multiple ranges for costs.

(a) method: 95.0 percent LSD

Concept	Cases	Mean	Homogeneous groups
Financing	55	1876.71	X
Operation	55	133492	X
Delivery time	55	138243	X
Production	55	180534	X
Raw material	55	203129	X
Quality	55	366922	X
Transportation	55	840106	X

(b)

Contrast	Sig.	Difference	+/− limits
Quality, financing	*	365045	39520.0
Quality, raw material	*	163793	39520.0
Quality, operation	*	233430	39520.0
Quality, production	*	186388	39520.0
Quality, delivery time	*	228679	39520.0
Quality, transportation	*	−473184	39520.0
Financing, raw material	*	−201252	39520.0
Financing, operation	*	−131616	39520.0
Financing, production	*	−178657	39520.0
Financing, delivery time	*	−136366	39520.0
Financing, transportation	*	−838230	39520.0
Raw material, operation	*	69636.7	39520.0
Raw material, production		22595.4	39520.0
Raw material, delivery time	*	64886.1	39520.0
Raw material, transportation	*	−636977	39520.0
Operation, production	*	−47041.3	39520.0
Operation, delivery time		−4750.54	39520.0
Operation, transportation	*	−706614	39520.0
Production, delivery time	*	42290.8	39520.0
Production, transportation	*	−659573	39520.0
Delivery time, transportation	*	−701863	39520.0

* indicates a significant difference.

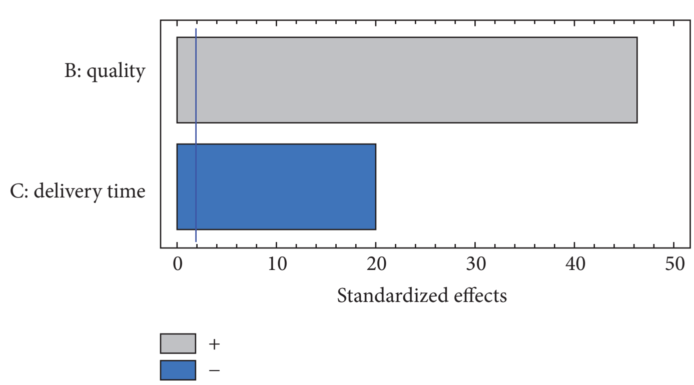


Figure 5: Graph of main effects for profit.

Table 8: Percentages of costs.

Capacity	Quality	Delivery time	Interest rate	Quality	Delivery time	Raw material	Production	Transportation	Operation	Interest rate
Low	Low	Low	Low	**32.1%**	**1.0%**	**10.0%**	**8.9%**	**41.2%**	**6.7%**	**0.09%**
High	Low	Low	High	**32.1%**	**0.9%**	**10.0%**	**8.9%**	**41.7%**	**6.2%**	**0.09%**
Low	High	Low	High	**4.4%**	**1.1%**	**14.2%**	**12.3%**	**58.5%**	**9.5%**	**0.11%**
High	High	Low	Low	**4.1%**	**1.0%**	**14.2%**	**12.5%**	**59.2%**	**8.9%**	**0.11%**
Low	Low	High	High	**29.7%**	**11.4%**	**8.7%**	**7.9%**	**36.2%**	**6.0%**	**0.09%**
High	Low	High	Low	**30.2%**	**10.5%**	**8.9%**	**8.0%**	**36.6%**	**5.8%**	**0.09%**
Low	High	High	Low	**5.0%**	**15.0%**	**11.9%**	**10.7%**	**49.0%**	**8.2%**	**0.12%**
High	High	High	High	**4.9%**	**13.4%**	**12.3%**	**10.9%**	**50.7%**	**7.7%**	**0.12%**
Medium	Medium	Medium	Medium	**18.9%**	**8.3%**	**10.9%**	**9.7%**	**45.0%**	**7.2%**	**0.10%**

Table 9: Number of facilities used per echelon and scenario.

Instance				Number of suppliers		Number of plants		Number of distribution centers	
Capacity	Quality	Delivery	Interest rate	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
High	High	High	High	40	40	30	30	23	29
High	High	Low	Low	37	40	30	30	21	24
High	Low	High	Low	40	40	29	30	24	28
High	Low	Low	High	37	40	30	30	22	29
Low	High	High	Low	40	40	30	30	27	30
Low	High	Low	High	40	40	30	30	26	28
Low	Low	High	High	40	40	30	30	27	30
Low	Low	Low	Low	40	40	30	30	24	30
Medium	Medium	Medium	Medium	40	40	30	30	23	30

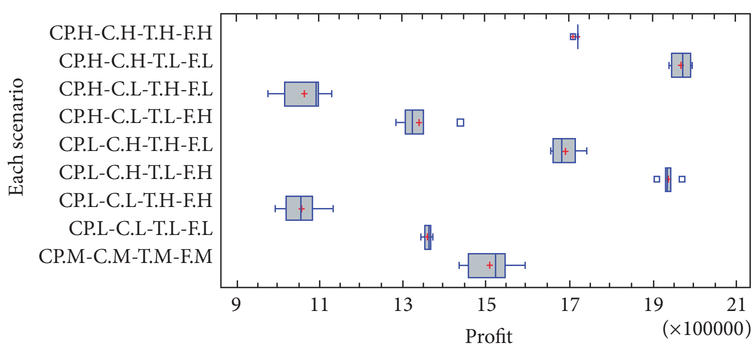


Figure 6: Box-and-whisker plot of profit.

relationships with all the rest of the factors, and a domino effect is generally observed when quality is improved. From this, we can argue that the quality performance can be even more significant than some logistics costs in reaching an adequate profit.

(vii) In this case, regarding costs, transportation yields the highest impact, followed by quality and then the cost of raw material. This is especially true in plants with operations relatively unchanging.

(viii) According to what has been observed, the two factors that most influence the value of the objective function are firstly the quality and then the delivery time. In fact, the quality factor has a little more than double the influence over profit than the delivery time. In this specific instance, the interactions between factors are not significant.

(ix) The exposed analysis has been done for a single time period. This time period can be as short or as long as the consideration of the demand and also according to the nature of the location decisions, which are usually long-term.

5. Conclusions

This paper proposes and studies a network design problem for a four-level supply chain (suppliers, plants, distribution centers, and end customers), where decisions include opening facilities (plants and distribution centers), supplier selection, and flows between the existing echelons. The problem is formulated as a mixed-integer linear programming model that maximizes the system profit depending on the sales price of the end products and the underlying system costs. The latter involve costs of operating facilities, transportation, raw material acquisition, and production activities. Additionally, a main contribution of this work is adding to the model the quality, delivery time, and financing aspects. The model maximizes the profit of the system in order to meet customer demand for finished products.

One primary and novel contribution of this work is the statistical analysis by designing experiments related to the impact on the system profit caused by changes in the levels of capacity, quality, delivery time, and interest rate for each of the actors involved in the supply chain. The results of the statistical analysis show that the transport cost component contributes most to the total cost, affecting the profit. However, regarding variability, the most important factor is

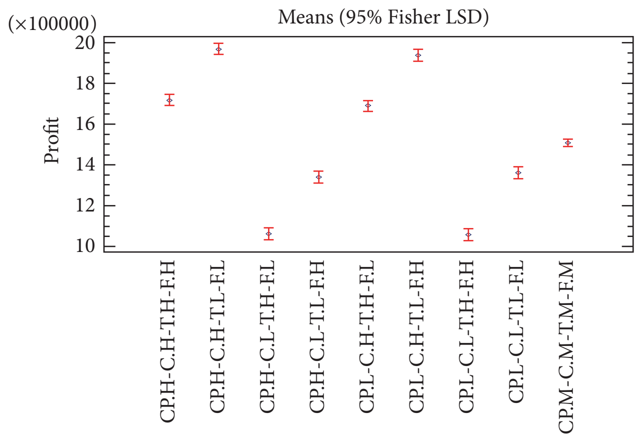


Figure 7: Means graph.

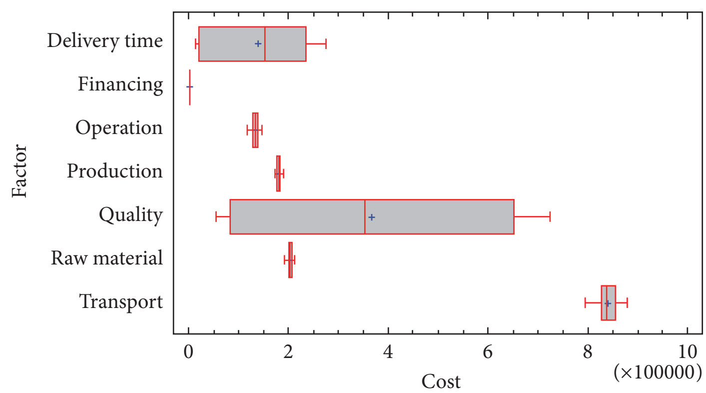
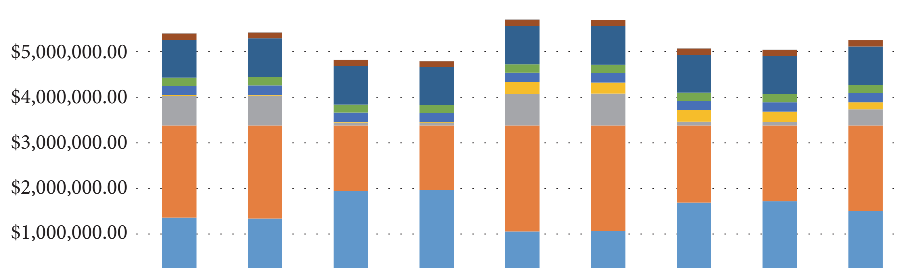


Figure 8: Box-and-whisker plot of costs.



	I.R. low D.T. low Q. low Cap. low	I.R. high D.T. low Q. low Cap. high	I.R. high D.T. low Q. high Cap. low	I.R. low D.T. low Q. high Cap. high	I.R. high D.T. high Q. low Cap. low	I.R. low D.T. high Q. low Cap. high	I.R. low D.T. high Q. high Cap. low	I.R. high D.T. high Q. high Cap. high	I.R. med D.T. med. Q. med. Cap. med.
Interest rate	$1,844.40	$1,747.87	$1,655.34	$1,502.55	$2,195.02	$1,980.45	$2,035.92	$1,938.59	$1,914.56
Operation	$136,256	$126,928	$136,191	$125,320	$138,975	$133,240	$138,920	$127,206	$135,125
Transportation	$832,004	$850,951	$842,811	$835,318	$840,620	$848,430	$827,294	$840,946	$840,930
Production	$178,788	$181,096	$177,191	$175,918	$182,851	$184,320	$181,272	$181,497	$180,978
Raw material	$201,599	$204,765	$204,376	$200,467	$202,948	$205,726	$200,148	$203,940	$203,482
Delivery time	$20,584.5	$19,327.6	$16,054.1	$14,683.1	$264,412	$244,240	$254,161	$222,891	$154,772
Quality	$647,879	$654,540	$62,696.0	$57,216.6	$690,396	$699,020	$84,562.6	$81,746.5	$352,695
Total cost	$2,018,95	$2,039,35	$1,440,97	$1,410,42	$2,322,40	$2,316,95	$1,688,39	$1,660,16	$1,869,89
Profit	$1,360,04	$1,339,64	$1,938,02	$1,968,57	$1,056,59	$1,062,04	$1,690,60	$1,718,83	$1,509,10

Figure 9: Profit, total costs, and subcosts.

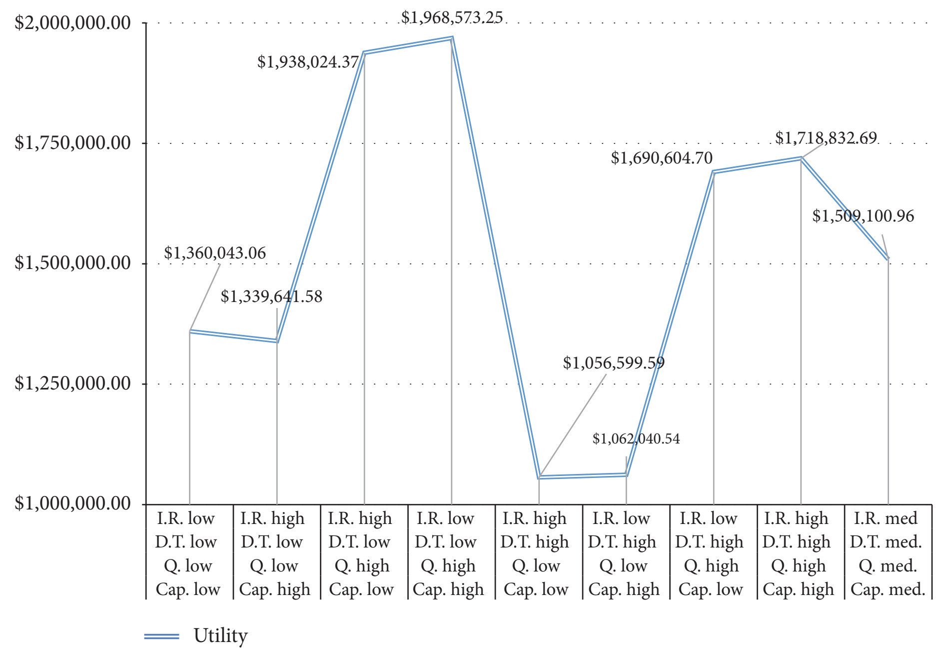


Figure 10: Total profit.

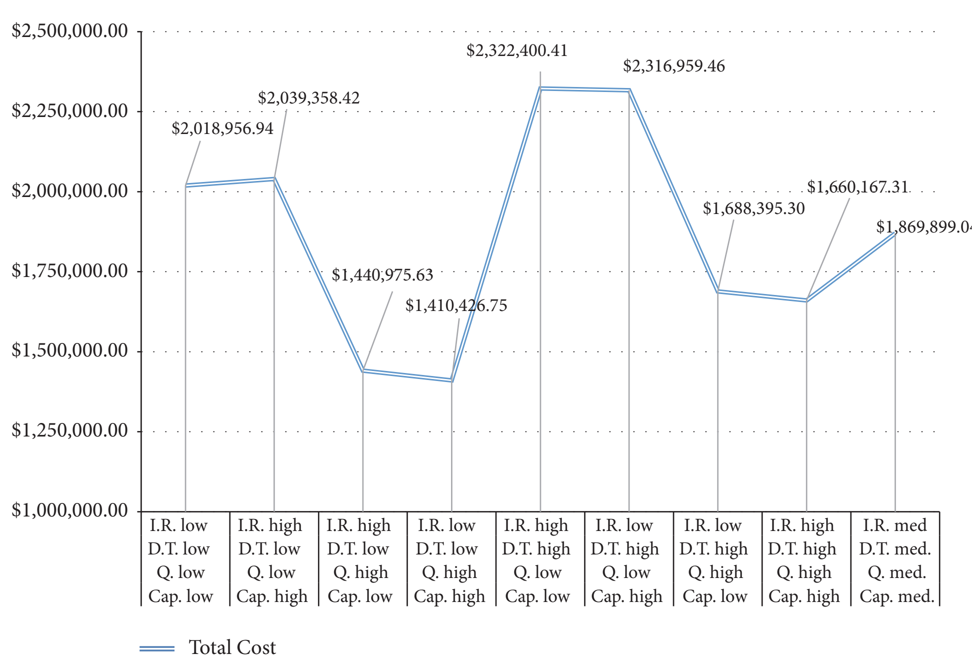


Figure 11: Total costs.

quality, followed by the effect of delivery time. Therefore, a policy is recommended in which, first, the variability of the quality in the supply chain is controlled and then care is taken regarding the variability produced by the delivery time. If it is possible to reduce transportation costs, higher profitability can be achieved. It can be observed that the factor that has less influence is the financing caused by the interest rate.

Results obtained in this paper are conditioned to the specific instance considered, with the specific parameters assumed. Thus, the yielded managerial insights cannot be easily extended to any other case, which may face different cost interactions. In each treatment, the level of each factor is set for the entire applicable scope in the supply chain, but with differences in parameters for different actors within the same echelon. In this way, the MILP optimizer drives the flow to laggard performers sometimes to keep up with the constraints. However, the pattern (laggard and best-in-class actors) between replicas, for the level change, is not conserved but is done randomly. This impedes a deeper analysis for particular cases, although the original scope

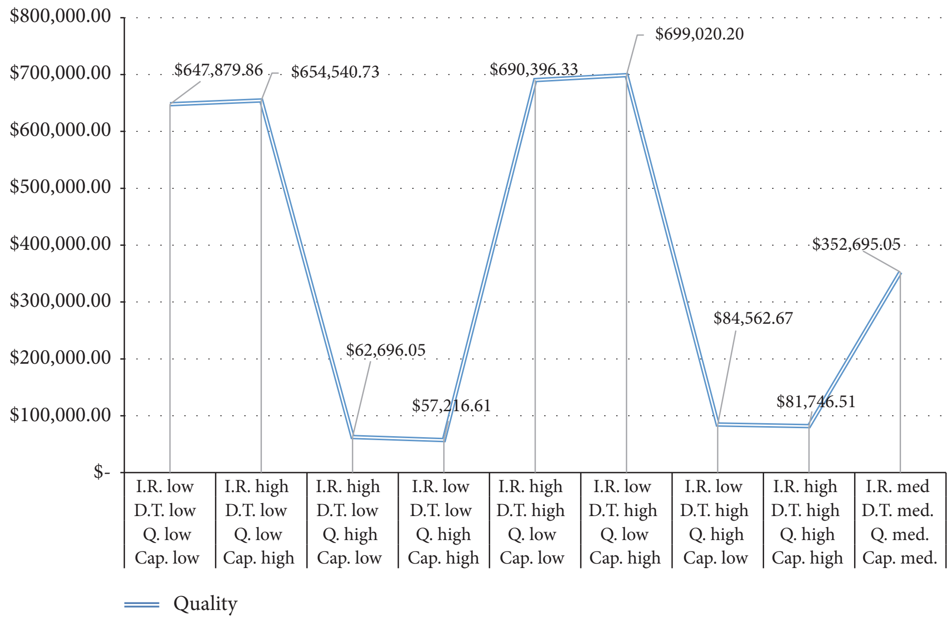


Figure 12: Quality cost.

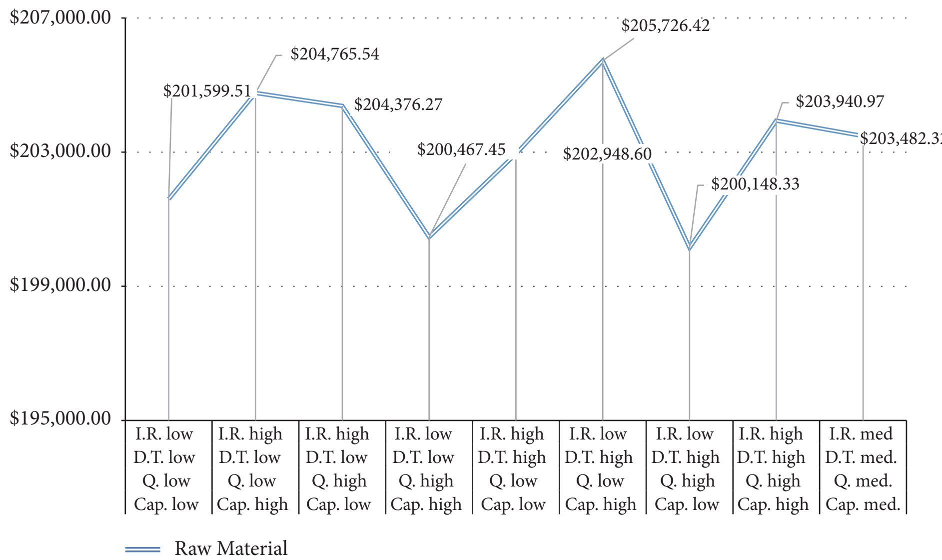


Figure 13: Raw material cost.

of the experiments aimed to know in a general way the effect of the factors on the organization and the performance (profit) of the supply chain. This is one key reason why the conclusions are not completely generalizable.

A main contribution of this paper stands on the methodological tool to analyze and optimize the supply chain network based on design of experiments and optimization techniques. As discussed, the proposed methodology can be easily extended to other case studies and problems, with different nature and features.

The application of design of experiments can be an alternative for stochastic programming, when the variability of parameters can be approximated by known probability distributions. The analysis allows measuring the effects of variability in the objective function, from main factors and interactions. A certain variability can be considered relatively high with respect to its own mean, but the effect can be minimal in the objective function, and this can be clarified by an analysis as proposed in this work.

Traditional methodologies on supply chain network literature are mainly focused on logistics cost minimization. In contrast, this research shows that quality costs may be very relevant and may present a great influence on system profit and supply chain network design and operation.

Several aspects can be considered as future research, to extend the applicability of this model. The most important are mentioned as follows: (i) it is intended to analyze the behavior of the supply chain by integrating learning curves for the

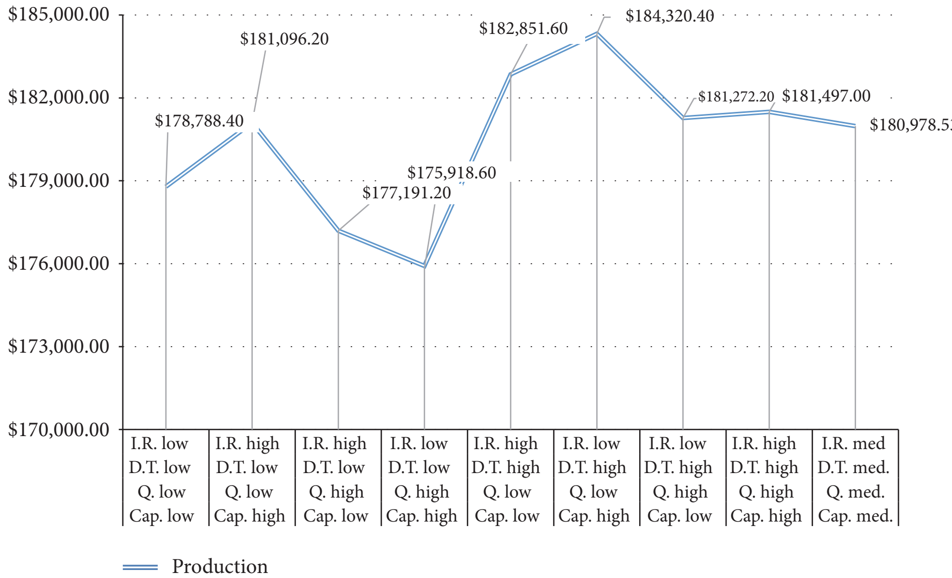


Figure 14: Production costs.

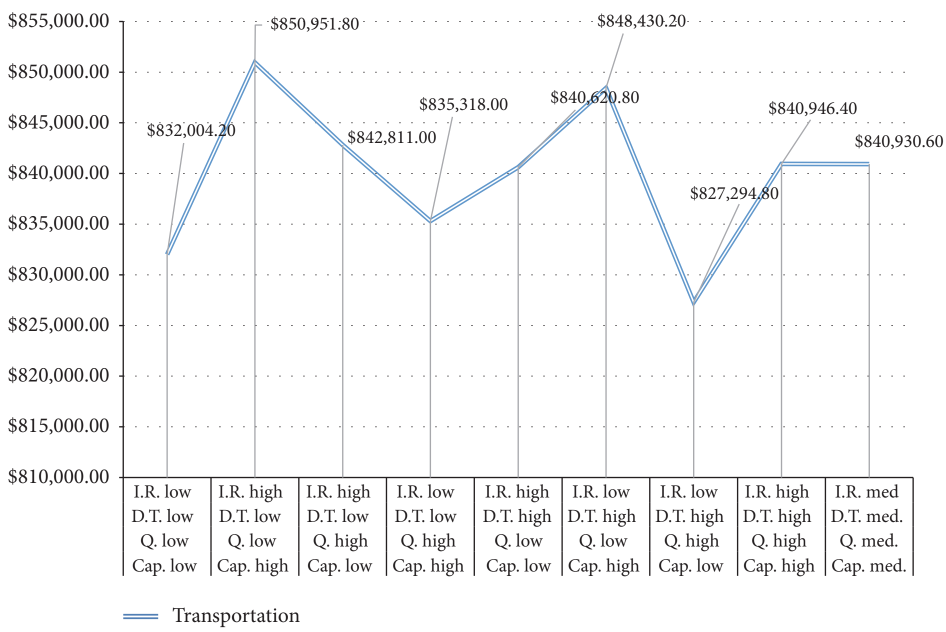


Figure 15: Transportation costs.

echelons, which may show the impact and the time it will take to incorporate a new participant in the supply chain. This can be applied when a supplier decides to enter into a different type of industry, in which it will have to go through a learning process to know the requirements of the new market. (ii) In this work, the quantities circulating through the supply chain have been considered as continuous variables. Typically, anyhow, many raw materials in most supply chains are handled in continuous measurement units, as liquids, chemicals, materials, and so on. It could be possible if necessary to transform this MILP to a full integer problem, considering its implications for yielding solutions, that may require the use of heuristics. (iii) For a different future case study, it is important to consider several costs that here were omitted, as other components of COPQ, like scrap costs. The same may be considered for the inventory holding costs and others. (iv) Stochastic demand and the implications derived from out-of-stock situations can be also considered in future analysis.

Disclosure

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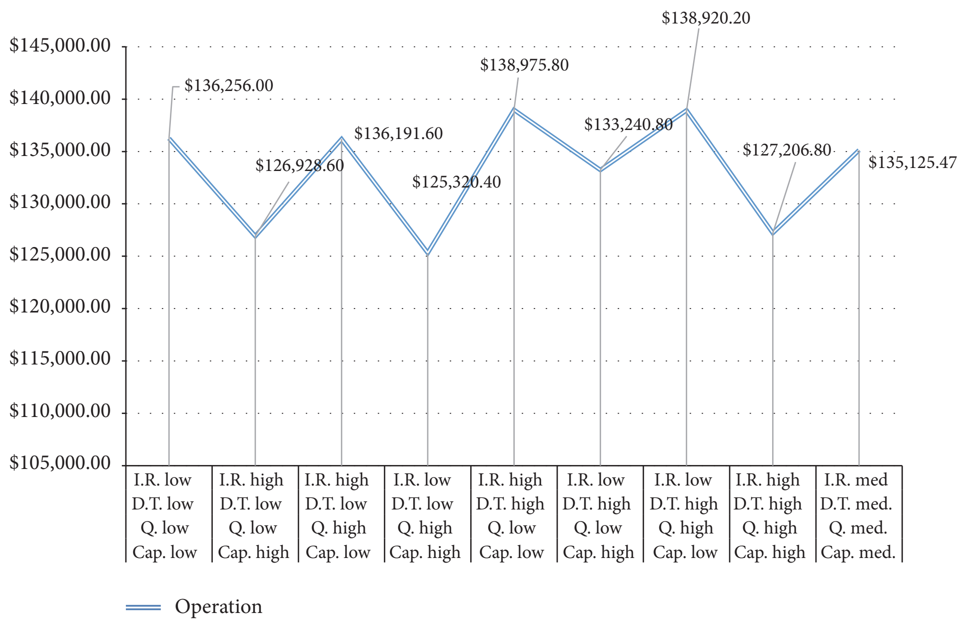

FIGURE 16: Operating costs.

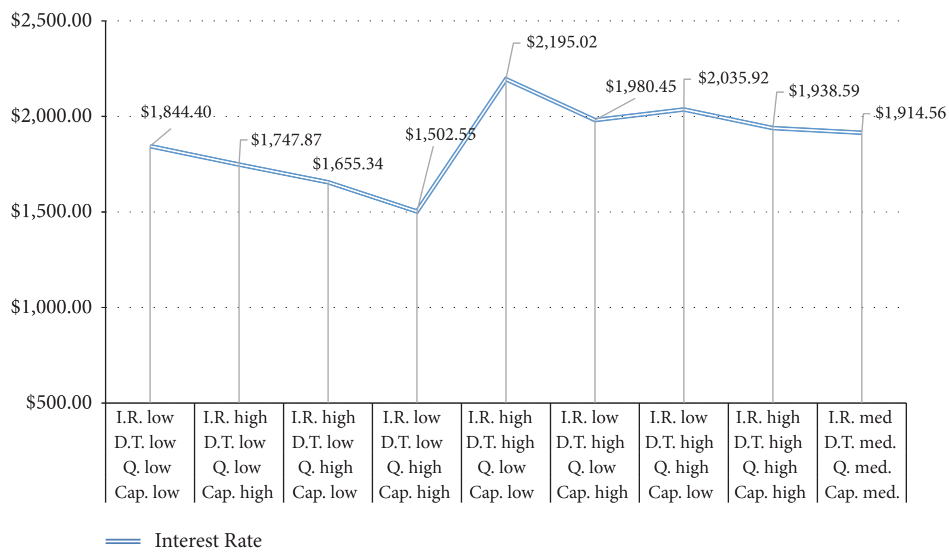

FIGURE 17: Interest rate (financial) costs.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Research Article

Impact of Business Interoperability on the Performance of Complex Cooperative Supply Chain Networks: A Case Study

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This paper proposes an agent-based model for evaluating the effect of business interoperability on the performance of cooperative supply chain networks. The model is based on insights from the Industrial Marketing and Purchasing network approach and the complex systems theory perspective. To demonstrate its applicability, an explanatory case study regarding a Portuguese reverse logistics cooperative supply chain network is presented. Face-to-face interviews and forms were used to collect data. The findings show that the establishment of appropriate levels of business interoperability has helped to reduce several non-value-added interaction processes and consequently improve the operational performance of the Valorpneu network. Regarding the research implications, this paper extends the current knowledge on business interoperability and an important problem in business: how business interoperability gaps in dyadic organizational relationships affect the network of companies that the two companies belong to—network effect. In terms of practical implications, managers can use the proposed model as a starting point to simulate complex interactions between supply chain network partners and understand better how the performance of their networks emerges from these interactions and from the adoption of different levels of business interoperability.

1. Introduction

It has been widely recognized that, in an era in which the traditional competition between companies has been replaced by competition between supply chain networks (SCNs) [1, 2], individual companies no longer compete as independent entities [3, 4] with unique brand names but instead as integral parts of SCN relationships [5, 6]. As a consequence of this change of the business context to a network-driven economy, companies have been increasingly forced to establish cooperation with SCN partners and other external entities [7] in order to obtain mutual benefits by sharing or partitioning work [8], increase efficiency, improve environmental performance [9], resolve common problems [10], enable market creation [11], provide superior value [12, 13], and establish a superior competitive position [14–16]. This in turn leads to cooperative SCNs, which are defined in this research as set of three or more companies with symbiotic interests that join and efficiently combine the most suitable set of skills and resources (e.g., knowledge, capital, and assets) for a time interval in order to achieve a common set of objectives [17].

However, because systems that support the operations in many companies were created independently [18], some challenges that SCN managers may face when it comes to establishing cooperation are misaligned and conflicting business goals, misaligned management approaches, misaligned business processes, misaligned methods of work, misaligned legal bases, multiple sources of data, heterogeneous and incompatible information technology, and so on (see [4, 19, 20]). To address these problems, business interoperability, often referred to as enterprise interoperability (e.g., [4, 21, 22]), has been widely pointed out as one of the main disciplines that has enabled companies to establish effective cooperation [23]. Its relevance to cooperative SCNs is evident. For example, Brunnermeier and Martin [24] estimated that, in the US automotive supply chain (SC), inadequate business interoperability delays the introduction of new models by at least two months and costs the members of this industry at least US $1 billion per year. Business interoperability can be defined as *"the ability of two or more business units, as well as of all systems within their boundaries and the external systems that they utilize or are affected by, to work together"* (adapted from [25]).

An analysis of the current literature reveals that, despite the high expectations concerning the effects of business interoperability on the performance of organizations, research in this field focuses mainly on developing architectures (e.g., [26, 27]), frameworks (e.g., [20, 28–30]), maturity models (e.g., [22, 31]), and methods/standards (e.g., [19, 32–35]). Indeed, as shall be discussed further below, only very little empirical research has been carried out regarding the analysis of the effects of business interoperability on the performance of companies, particularly in complex cooperative SCN contexts (see, e.g., [24, 36–39]).

An examination of these studies reveals that, despite their significance to the development of theory on business interoperability, they do not provide insights on how different levels of business interoperability in dyadic organizational relationships affect the performance of the two companies in the dyads and, more importantly, how different levels of business interoperability in dyadic organizational relationships influence the performance of the network that the two companies in the dyad belong to. In this research, the spread of the effects of different levels of business interoperability over the cooperative SCN is called network effect—a phenomenon that occurs in complex systems where the actions or behavior of a system's component have effects on the other system's components. Addressing the network effect in the analysis of the impact of business interoperability on the performance of cooperative SCNs is important because, as emphasized by Håkansson and Snehota [40], the impacts of a dyad relationship are not limited to the two companies in the dyad; that is, other entities and dyads may be impacted. Limiting the analysis only to the performance of the two companies involved in the dyads does not allow a great understanding of the true effect of business interoperability on the performance of cooperative SCNs. In addition, they do not provide any guideline about how to predict the effect of business interoperability on the performance of a new cooperative SCN for being designed and how improvements in the level of interoperability affect the network performance over time. A level of business interoperability is a concept that is used to characterize the state at which a business system can be situated in terms of interoperability with other business systems [31], that is, a measure of how interoperable two or more connected business systems are [28]. Defining certain levels of business interoperability in the analysis of the effects of business interoperability is important to distinguish different interoperability requirements and to serve as a guideline for improving the business interoperability performance of business systems [28, 41].

Another relevant gap is that those studies addressed the analysis of the impact of business interoperability by investigating the companies individually, assuming that no specific links are supposed to exist among the companies in the network. Put differently, the unit of analysis was set at the organizational level instead of at the dyad relationships level. As Johnston [42] (cited in [43]) emphasized, grounding on any individual company/dyad cannot offer any great understanding of the business interactions. To overcome the research gaps identified above, this research presents a model that can be used to analyze the effect of business interoperability on the performance of complex cooperative SCNs. In seeking to achieve this goal, the following research question was posed:

How can we analyze the effect of business interoperability on the performance of complex cooperative supply chain networks?

To address this research question, the following research stance was defined:

Agent-based simulation provides an effective set of tools for analyzing the effect of business interoperability on the performance of complex cooperative supply chain networks.

Agent-based simulation (ABS) is a modeling tool used by researchers from different areas of knowledge to understand and analyze complex patterns that result from the interaction of many individuals within an environment [44]. The justification for choosing ABS as the modeling tool to address the above research question is provided in Section 4.1.

The remainder of this paper is structured as follows: the following section discusses the concept of business interoperability and the aspects of the complex system theory (CST), following the development of an extended business interoperability framework and research hypotheses. The rationale for using ABS and the details of the ABS model are provided in the section thereafter. The paper goes on to test the applicability of the model through a case study regarding a Portuguese reverse logistics (RL) cooperative SCN and ends with the conclusions and suggestions for the forthcoming work.

2. Theoretical Foundations

2.1. Business Interoperability: An Overview. Interoperability has been mostly defined and addressed from the technical perspective (see [45]). This is revealed in one of the most cited definitions of interoperability [46]: *"the ability of two or more systems or components to exchange information and use the information that has been exchanged."* However, interoperability is not only an issue of exchanging information through information and communication technology (ICT) systems (e.g., [18, 45]). There are other dimensions such as interorganizational processes, culture, and the management of contractual issues between the business partners [8]. As a result, the concept of interoperability has been increasingly replaced by business interoperability in order to include the human and organizational elements (e.g., [28, 29, 32]). The definition of business interoperability adopted in this paper is the one provided in Section 1.

2.2. Business Interoperability Frameworks. The current literature includes many elements that have been identified in and around the business interoperability (e.g., [4, 26, 28, 29]), supply chain management (SCM) (e.g., [47–50]), business relationships (e.g., [51–53]), complex SCNs (e.g., [54–58]), and collaboration (e.g., [59–62]) literature as responsible for the relationships between two or more companies. In the context of this research, the elements of these literature strands are grouped into categories that are named dimensions of business interoperability. A dimension of business interoperability can be defined as the different aspects of business interaction that two or more companies can engage in (e.g., business strategy, management of external relationships, cooperative business processes, business semantic, and information systems) [29]. As implied in this definition, business interoperability is a multidimensional concept that can be viewed and approached from various perspectives, and therefore many frameworks have been proposed to reconcile all the perspectives, approaches, and directions, which are frequently different [63].

A review of the business interoperability literature suggests that there is no shortage of frameworks for modeling interoperability in different business contexts. Among the frameworks published so far, the Levels of Information Systems Interoperability (LISI) [41] is often regarded as the first significant initiative carried out to address interoperability (e.g., [31, 64]). However, it is often criticized due to its "strong" focus on the technical aspect of interoperability [31, 65]. Acknowledging this limitation, frameworks such as the IDEAS interoperability framework [66], the European Interoperability Framework [67], the ATHENA interoperability framework [68], the E-health interoperability framework [69], and the Framework for Enterprise Interoperability [70] have been developed to capture other aspects of business interoperability such as business strategy, business processes, and knowledge management. Although these have been pointed out as some of the most relevant interoperability frameworks (e.g., [22, 26]), they do not incorporate a number of factors associated with the network complexity, which limit their use or make it difficult in the analysis of interoperability in complex business network contexts. In the attempt to overcome this limitation, ATHENA [28] developed the business interoperability framework to support the analysis of collaboration between networked organizations, which has been used as the reference to develop the Zutshi et al.'s [29] framework. This framework captures eight dimensions of business interoperability, called business interoperability parameters, and further identifies subdimensions to allow measuring performance for each parameter (see [29]). In comparison with the frameworks mentioned above, ATHENA's [28] and Zutshi et al.'s [29] frameworks enable a more holistic approach to business interoperability as they incorporate a greater number of business interoperability factors, which are also better organized into five and eight categories, respectively. However, despite recognizing their contribution to the business interoperability literature, we argue that, in order to examine the interactions among companies in complex cooperative SCNs, a more holistic framework is needed. This is in line with Corella et al. [71], who stress that there are scarce practical examples of an SC interoperability framework that can be applied as a reference, and therefore more holistic frameworks must be designed to support the improvement of business interoperability performance. Zutshi et al. [29] also recognized that as the effects of business interoperability across multiple companies in a network need to be further explored, future investigations should adapt their framework in order to be used in a network-based context.

From our perspective, ATHENA's [28] and Zutshi et al.'s [29] frameworks have two relevant limitations. First, they do not capture all relevant dimensions of business interoperability and even those that are incorporated do not include all relevant subdimensions. For example, in the dimension business strategy, issues such as alignment and visibility of cooperation goals are missing. Trust and transparency are missing in the dimension of management of external relationships. Alignment, coordination, integration, flexibility, and monitoring are also missing in the dimension cooperative business processes. Also, they do not incorporate elements related to one essential dimension of business interoperability, that is, Information Quality (see [72]). With regard to this, note that the subdimensions of information quality (e.g., accuracy, timeliness, and completeness) were not incorporated in any of the business interoperability frameworks published so far. The second limitation is related to the design of these frameworks, which was not supported on any relevant network or complexity theory. We argue that as business interoperability in network-based contexts is a multidimensional construct consisting of many related dimensions and subdimensions, making the network even more complex, a network theory is needed to address such complexity. For this reason, this research is grounded on the CST, which advocates that complex systems, as are the examples of cooperative SCNs, should be analyzed in a holistic and systemic way (e.g., [73]) (see the next section).

2.3. Complex Systems Theory. As a relatively new research discipline, CST can be seen as a metatheory that deals with the research of complex systems [74, 75]. For example, in the SCM literature, it has been widely used as a theoretical lens for analyzing complex SCNs [76], providing theoretical frameworks for a number of SCN related publications (see, e.g., [54–58, 73, 77–80]).

The rationale for addressing CST in this research is not limited to the design of our business interoperability framework, which is associated with the aspect of decomposability. From the perspective of CST, as SCN systems are embedded in an open and dynamic environment and interact with it [54], there are eight major aspects that must be taken into account when modeling this type of systems (see [54, 81, 82]): decomposability, dimensionality, reflexivity, nonlinearity, emergence, ability to learn, self-organization, and quasi-equilibrium. Indeed, these aspects have a number of implications for this research. For example, the aspect decomposability, which helps to separate subsystems from one to another [81], is important to decompose the business interoperability construct into detailed dimensions and subdimensions that can be clearly understood, measured, and managed. This facilitates the design of the extended business interoperability framework (see Figure 1) as well as the measurement of its constructs through a maturity model. Dimensionality addresses the degree of freedom that individual companies within the cooperative SCN have to

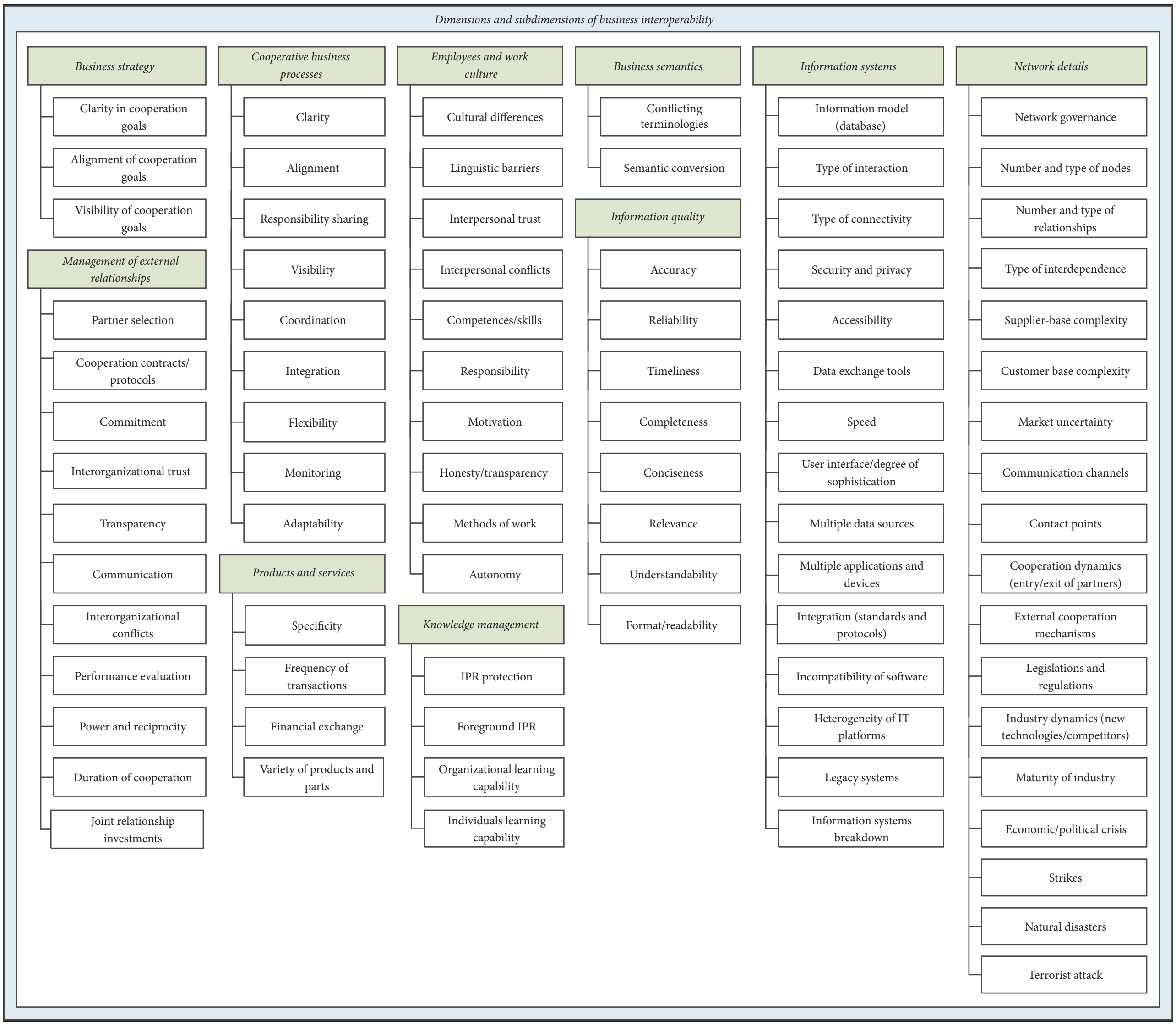


Figure 1: Extended business interoperability framework (adapted from [29]).

behave autonomously [81]. In the scope of this research, it is important to understand the dimensionality of the cooperative SCNs because [81] (1) SCNs with high dimensionality tend to be difficult to control and tend to be too uncooperative harnessing the achievement of the cooperation goals and (2) too less dimensionality implies lees autonomy to invest on innovative cooperation mechanisms, also hampering the value that business interoperability can provide to the whole SCN. Therefore, it is important to measure and maintain cooperating partners freedom in efficient levels.

Reflexivity suggests that as cooperative SCNs are frequently changing and adapting to new market and/or internal needs, the behaviors of each agent in the network have effects on the other agents around it [81]. For example, by closing emergent interoperability gaps, establishing or eliminating relationships in the cooperative SCN, the performance of the other agents in the network can be affected. This in turn might force the other agents to act in response to those changes, hence causing a reflexive impact on the performance of the whole network. There is an interoperability gap when the current level of business interoperability on a particular situation of interaction does not match the required level. Nonlinearity suggests that cooperative SCNs contain critical nonlinear characteristics where a small change can be magnified to impact the whole network [81]. For example, "changes to the master schedule quantities can have unpredictable, nonlinear impacts on the individual material plans due to differences in planning lead times, lot-sizing rules, and inventory levels for lower level components" [57]. Interoperability gaps in a given dyad relationships may have different impacts on different dyads/companies. Emergence is the arising of new, unexpected patterns, structures, processes, or properties in the whole network [54]. These highly structured collective behaviors, which are not easy to predict by knowing only the behavior of the individual agents, come from the interactions between these individual agents [83]. With reference to cooperative SCNs, two of the emergent phenomena that can arise are demand amplification and inventory swing. For example, the delays downstream and decisions in an SC often lead to amplifying a nondesirable effect upstream, a phenomenon usually called the "*bullwhip*" effect [82]. Another key idea of emergent properties is that the outcome of those interactions leads to the concept of synergy, suggesting that the sum of the individual parts is more than the system as a whole [84]. Again, with reference to this study, the establishment of appropriate levels of business interoperability in the dyad relationships throughout the cooperative SCN might enable effective interactions between its partners, hence resulting in a performance that might be higher than the sum of the performance achieved in each dyad. Note that this aspect, along with reflexivity and nonlinearity, reinforces the importance of addressing the network effect in the analysis of the impact of business interoperability on the performance of cooperative SCN, as discussed in Section 1.

Ability to learn suggests that intelligent systems, as are the examples of cooperative SCNs, are able to adapt their individual capabilities and improve their performance as experience accumulates [81]. In the ambit of this research, it implies that cooperative SCNs must retain past knowledge on their interoperability experience and use it to learn how to improve their interoperability performance. This requires effective sharing and storage of information on the interoperability experience, which can be used to support decision-making regarding the interoperability mechanisms to be implemented. Self-organization occurs when, based on a certain degree of intelligence, a system uses acquired knowledge to change its internal structure in order to better interact with its environment and adapt automatically to external changes [81]. In the specific case of cooperative SCNs, the interactions among their companies are affected by a set of external events such as the introduction of new legislations and regulations, introduction of new technologies, natural disasters, and economic and political crisis. These events may cause disruptions in the cooperative SCN operations and, in this situation, the cooperative SCN must use its experience to self-organize and recover to a business interoperability state that is equal to or greater than the one when the disruptions occurred.

Last, a system is in quasi-equilibrium when it is prevented from collapsing into randomness but still retains enough freedom to evolve and adapt to the environment whenever needed [81]. In the ambit of this research, it refers to the ability of a cooperative SCN to oscillate between a state of network equilibrium where companies interact normally with interoperable relationships and nonequilibrium characterized by a network with fuzzy relationships or with interoperability issues such as misaligned objectives, business processes and information systems, interorganizational conflicts, and responsibilities not well defined. It is therefore necessary to have in place effective interoperability mechanisms in order to minimize these oscillations and maximize the time cooperative SCNs are operating linearly profiting from a maximum efficiency from the interoperable relationships [81].

2.4. Agent-Based Simulation. ABS is a relatively new computational method that enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment [85]. It is an approach to modeling complex systems composed of interacting, autonomous agents [86], and to investigating aggregate phenomena by simulating the behavior of individual agents, such as consumers or organizations [44]. In other words, it is a method for modeling Multiagent Systems (MAS) which consist of a set of elements (agents) characterized by some attributes and behaviors, which interact with each other through the definition of appropriate rules in a given environment [87]. Specifically, a MAS is defined by Monostori et al. [88] as a network of agents that interact and typically communicate with each other. Agents refer to any autonomous entity with its own properties, behaviors [44], and decision-making capability [89].

According to Giannakis and Louis [90], the agent-based technology is acknowledged as one of the most promising technologies for effective management of complex systems such as SCNs due to the vital properties of agents, which are summarized, for instance, in Michael and Jennings [91], MacAl and North [86], and Barbati et al. [87]:

(1) *Autonomy*. Agents are able to operate without the direct intervention of humans or others and have some kind of control over their actions and internal state. In other words, agents are aware of their environment operating and control their own actions as well as internal states in order to fulfil their objectives. In particular, the user does not interfere with their decision-making, after they specified their rules.

(2) *Social Ability*. Agents are able to interact with other agents (and possibly humans) via some kind of agent-communication language or common actions.

(3) *Reactivity*. Agents are able to perceive their environment, including other agents, and they are able to react on the basis of these perceptions; that is, they are able to respond in a timely fashion to changes that occur in their environment.

(4) *Proactiveness*. Agents do not simply respond to changes in their environment but can initiate actions in order to satisfy their specified objectives.

3. Hypotheses Development

3.1. Framework of Reference. The framework developed in this research to support the analysis of the effect of business on the performance of cooperative SCNs (see Figure 1) is an extended version of Zutshi et al.'s [29] framework. It was designed to overcome the limitations of the frameworks discussed in Section 2.2. The rationale for choosing Zutshi et al.'s [29] framework as the reference is that it draws upon the literature review of most of the previous interoperability frameworks and because it focuses on the dimensions of

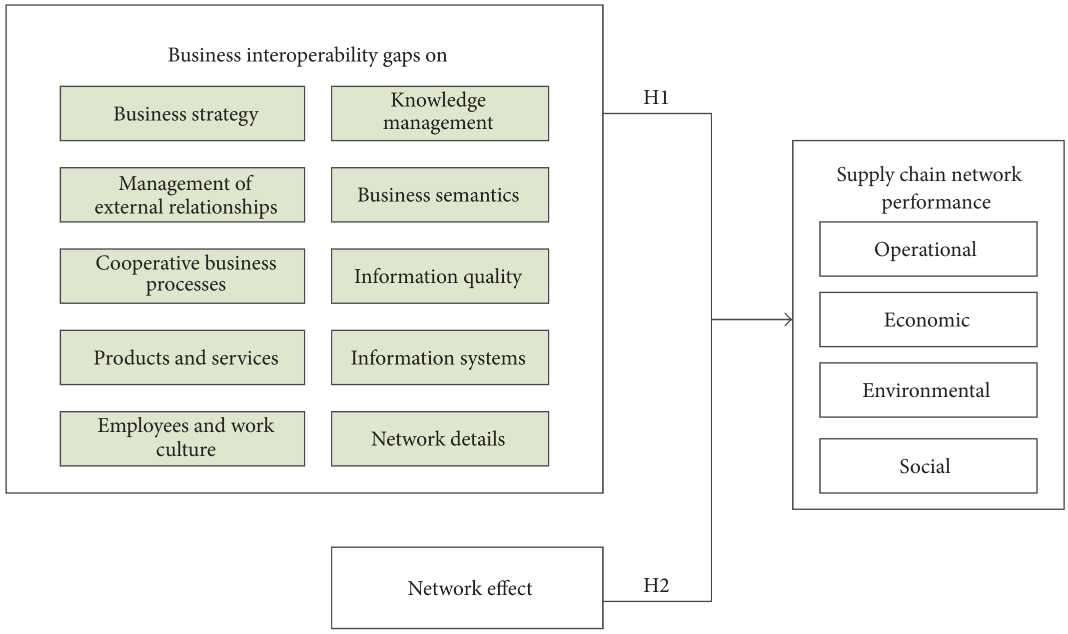


Figure 2: Conceptual framework.

business relationships between collaborating partners, which can also be applied to the context of cooperation. Given that business interoperability is a multidimensional concept, it has been built on the following assumption:

Business interoperability is a multidimension concept that considers not only the information systems configuration characteristics but also other dimensions such as management of external relationships, business strategy, cooperative business processes, employees and work culture, products and services, knowledge management, information quality, business semantics, and network details.

The dimensions of business interoperability included in Figure 1 will be used as constructs in the development of the research hypotheses, the theoretical framework (see Figure 2), and the theoretical ABS model (see Section 4.2). The description of each dimension and subdimension of business interoperability provided in Figure 1 can be found in Cabral [92]. Given that most of the constructs included in that framework are abstract and their integration in the ABS model depends on the business interoperability requirements of the cooperative SCN under analysis, the Axiomatic Design Theory [93, 94] was used to decompose them into detailed constructs that can be easily measured and modeled (see Figure 3). The Axiomatic Design Theory is a design methodology that is used by designers to decompose and structure the components of a complex system in a logical and rational way [94].

3.2. Linking the Levels of Business Interoperability to SCN Performance. Business interoperability has been regarded as an important source of business value [36] and a challenge affecting the success of companies' deployment [95]. For example, Brunnermeier and Martin [24] analyzed the US automotive SC and concluded that imperfect interoperability is very costly and that fixing its problems may help to improve the performance of the industry by minimizing cycle time and cost. Jardim-Goncalves et al. [96] stress that business interoperability is a factor with high impact on the productivity of both the public and private sector, impacting the overall quality, cost of transactions, and yield time, as well as the design of industrial processes and digital public services.

Indeed, empirical evidence shows that business interoperability has a significant effect on the business performance, mainly on the economic and operational dimensions. A classic example is Brunnermeier and Martin's [24] study, mentioned in Section 1. Another example is the Loukis and Charalabidis' [36] study, which concluded that the adoption of information systems interoperability standards such as proprietary, industry-specific, and eXtensible Markup Language- (XML-) based (http://www.w3.org/XML/) ones has a significant positive impact on the four dimensions of performance proposed by the balanced scorecard (customers, learning and innovation, financial, and internal business processes). Additional empirical studies on the impact of interoperability are Gallaher et al. [37], Gallaher et al. [38], and White et al. [39]. These studies suggest a link between business interoperability and economic/operational performance of cooperative SCNs. The performance of a business system refers to how efficiently and effectively it is able to transform the inputs to outputs [28]. Economic performance relates to the SCNs' ability to reduce costs associated with purchased materials, energy consumption, waste treatment, waste discharge, and fines for environmental accidents, while operational performance relates to the SCNs' capabilities to

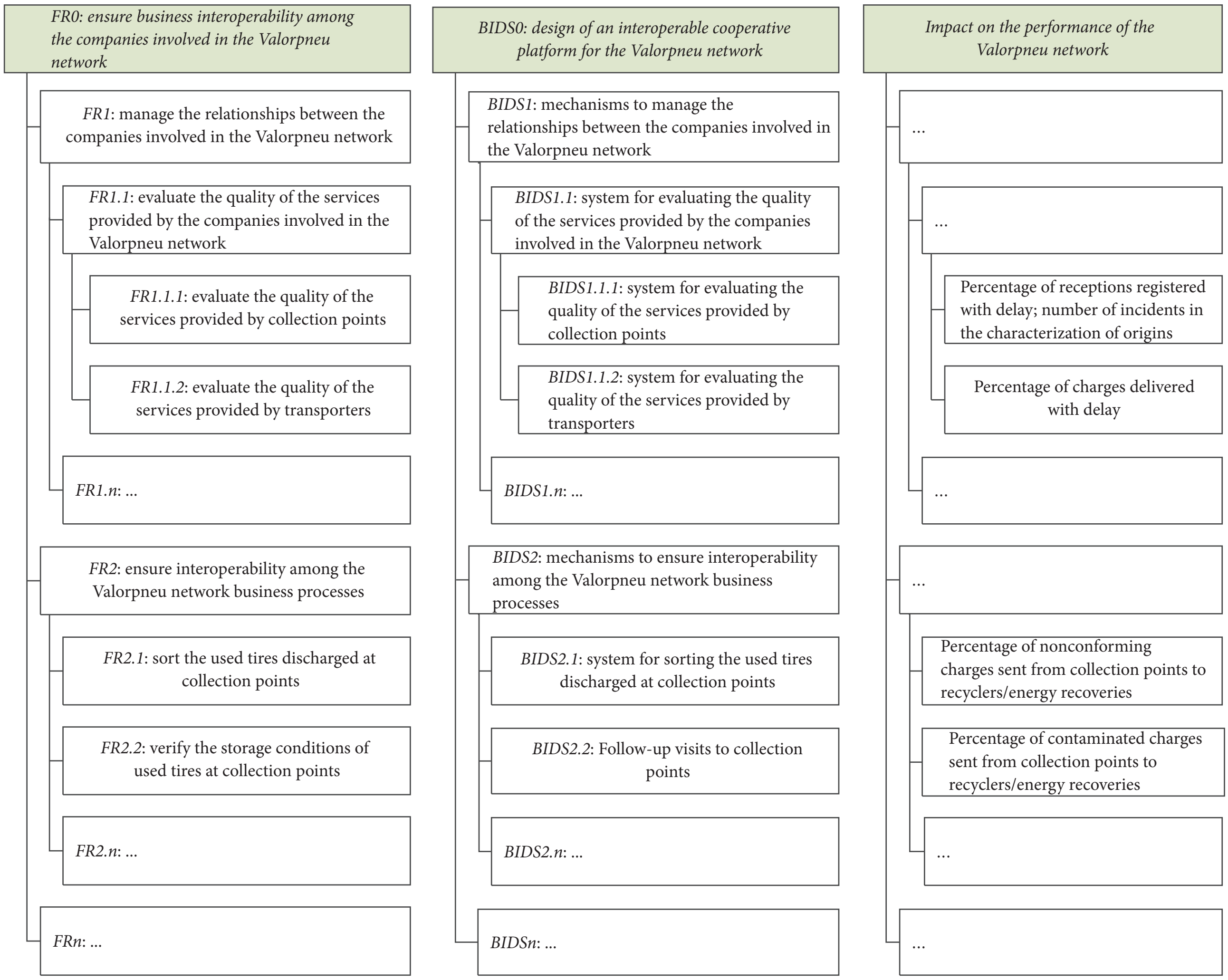


Figure 3: Link between FRs, BIDSs, and performance measures.

more efficiently produce and deliver products or services to customers [9].

Common to the above studies is the focus on the information systems' configuration characteristics. The literature mentioned earlier in this paper highlighted the need to take a holistic approach in addressing business interoperability, mainly in the context of cooperative SCNs. This is in line with Loukis and Charalabidis' [36] recommendation to study empirically the value added not only of "technical interoperability" but also of "organizational interoperability" as well and their complementarities. For example, the impact of complexity on the performance of SCNs, which is usually addressed in the SCM literature (see [57]), has never been addressed in the literature on the analysis of the effect of business interoperability on the performance of networked companies.

Also, the research approaches employed in those studies do not allow "pragmatic" testing of the effect of diverse levels of interoperability on the performance of networked companies. Perhaps for this reason, the findings of Loukis and Charalabidis [36] indicated that future research on the business value of information systems should take into account the levels of interoperability that a company's information and communication technology (ICT) infrastructures provide as high-priority variables. Testing the effect of different levels of business interoperability is important because a higher level of interoperability does not necessarily mean a sign of maturity or excellence, since the "optimum level of interoperability" depends on whether the accumulated investments on business interoperability solutions outbalance the benefits, that is, whether it "fits" the interests of the stakeholders [28]. Therefore, the "optimum level of interoperability" has to be judged based on the individual requirement of each situation of interaction; that is, if a low level of business interoperability perfectly matches the situation, costly improvements to existing systems may be unwarranted [28]. In this study, "the optimum level of business interoperability" is reflected in the measure of the gap between the actual level of business interoperability (ALBI) and the required level of business interoperability (RLBI) (see (1)).

Another important limitation of the previous studies is the strong emphasis on the operational and economic dimensions of business performance. Note that operations management has matured from a field that myopically focused only on these two dimensions to one that comprehensively addresses the broader social and environmental issues that organizations face nowadays [97]. Corresponding to these trends and the fact that SCNs operate in open and dynamic environments (see Section 2.3), we argue that expected performance outcomes of business interoperability are not only operational and economic matters but also environmental and social ones. For example, Gallaher et al. [38] argue that inadequate interoperability in construction industry leads to missed opportunities that could generate valuable benefits for the public at large. In manufacturing industries, business interoperability problems impact society's economic welfare in the following ways: (1) increasing the cost of designing and producing final products and (2) delaying the introduction of new final products—an increase in the cost of designing and producing a new aircraft or automobile may result in an increase in the equilibrium price of their respective markets [37]. These arguments suggest that business interoperability also affects the social performance of SCNs. Social performance relates the ability of cooperative SCNs to meet their legal or social obligations that integrate societal concerns into their business operation and their interactions with their stakeholder groups such as employees, local communities, and the government [98, 99].

Regarding the environmental performance, which is defined as the ability of cooperative SCNs to reduce air emissions, effluent waste, and solid wastes and the ability to decrease consumption of hazardous and toxic materials [9], ATHENA [28] advocates that external contingences such as environmental legislations affect the business relationships and as a result may affect companies' environmental performance. For example, in the case of the Waste Electrical and Electronic Equipment (WEEE) directive, manufacturers are enforced to be responsible for the entire lifecycle of their products [100], contributing to improving their environmental performance. There is also evidence that the implementation of Green Supply Chain Management (GSCM) in Asian countries, such as India, China, Malaysia, Taiwan, South Korea, Thailand, and Indonesia, is partially influenced by a cultural norm called Guanxi, which plays a key role in relationship governance within SC activities by helping companies to better manage their relationships while they green their SCs [101] and improve their environmental performance. In addition, issues such as absence of cleaner production technologies and underdevelopment of recycling technology may inhibit the establishment of GSCM (e.g., [102]) or reverse logistics (e.g., [103, 104]), which in turn might contribute to reducing companies' environmental performance.

An analysis of the SCM literature (e.g., [102, 105]) also reveals that internal business interoperability drivers such as collaborative transportation, coordination of raw materials and components from suppliers to manufacturers, exchange of design specification and environmental requirements, involvement of suppliers in the development and design stage, cooperation with vendors to standardize packaging, integration between focal company engineers and suppliers' designers, certification of suppliers/vendors' environmental management system, organization of environmental seminars and training for suppliers, system for encouraging suppliers to take environmental initiatives, system for rewarding environmental initiatives taken by suppliers, and environmental auditing of suppliers/vendors can help SCN partners to eliminate or at least reduce emissions, energy, hazardous chemical, and solid waste. These arguments suggest that both external contingences and internal business interoperability drivers are related to the environmental performance of SCNs. Underpinned by the above theoretical discussions, the following hypothesis is postulated.

Hypothesis 1. Business interoperability gaps in a dyad relationship are negatively related to the performance of the two companies involved in the dyad.

3.3. Linking Network Effect to SCN Performance. As discussed earlier in this paper, there is a need to address the network effect in the analysis of the effects of business interoperability on the performance of cooperative SCNs. Indeed, the literature on business interoperability and SCM suggests that the effect of the levels of business interoperability in dyad relationships is not limited to the two companies in the dyads, although this aspect has not been empirically investigated. For example, Gallaher et al. [38] argue that inadequate interoperability in dyad relationships increases the cost burden of construction industry and leads to missed benefits for this industry. White et al. [39] stress that small improvements in business interoperability in dyad relationships can produce disproportionately large improvements in SC function. On the other hand, issues such as order cancellations, production problems, shipment delays, and forecast revisions at any step in an SC may interrupt information and physical flows, forcing suppliers to adjust their planning (White et al. [39]), which in turn might have an impact on the whole network. However, although these arguments suggest that the levels of business interoperability in dyad relationships is expected to affect the performance of network of companies to which the dyads belong to, empirical research on the analysis of the effect of business interoperability on performance does not explain how this impact can be analyzed nor which network theories can help to understand such phenomenon [24, 36].

To address this gap, this study takes the perspectives from the Industrial Marketing and Purchasing (IMP) network approach and specific aspects of CST to connect the network effect to the performance of cooperative SCNs (see Hypothesis 2). The IMP network approach was developed in the IMP group [40, 106, 107] in an attempt to account for the complex reality of interorganizational exchanges [108]. It was developed based on the assumption that the initial IMP interaction model (e.g., [109]) is not appropriate to explain the effect of connectedness among dyadic business relationships because its emphasis is generally on a dyad relationship. In short, the basic assumption of the IMP network approach is that relationships should not be viewed as created and developed in isolation but as part of a broader network of interdependent relationships [40]. The implication of this network approach to this study is that in order to understand better the effect of business interoperability on the performance of networked companies, it is necessary to analyze not only how business interoperability affects the performance of the two companies in the dyad (Hypothesis 1) but also how it affects the whole network. For these reasons, the IMP network approach has been considered as one of the theoretical perspectives supporting the development of Hypothesis 2.

In addition to the IMP network approach, we argue that the principles of CST can also help us to understand the connection between the network effect of interoperability gaps and the performance of cooperative SCNs. Given the complex nature of SCNs (e.g., [54]), Agostinho and Jardim-Goncalves (2015) suggest that some complexity theory is perceived as a means of simplifying them. Indeed, SCNs exhibit emergent or synergistic properties that are difficult to be understood without reference to subcomponent relationships [81]. Putting it in the scope of this study, the emergent impact of business interoperability gaps in dyad relationships cannot be properly understood without an analysis of the network effect. We argue that such analysis must necessarily be grounded on the discipline of complex systems, particularly on the CST. The specific aspects of CST that allow us to transit to Hypothesis 2 and connect network effect to SCN performance are reflexivity, nonlinearity, and emergence (see Section 2.3).

Note that the insights from these three aspects of CST are in line with the principles of the IMP network approach. In sum, the insights from these two network theories suggest that the gaps between the ALBI and RLBI in dyad relationships have a reflexive and nonlinear effect on the performance of other agents belonging to the network and an emergent effect on the performance of the cooperative network as a whole. Therefore, based on the above review of the literature, the following hypothesis is articulated.

Hypothesis 2. Business interoperability gaps in a dyad relationship are negatively related to the performance of the cooperative SCNs that the dyad belongs to.

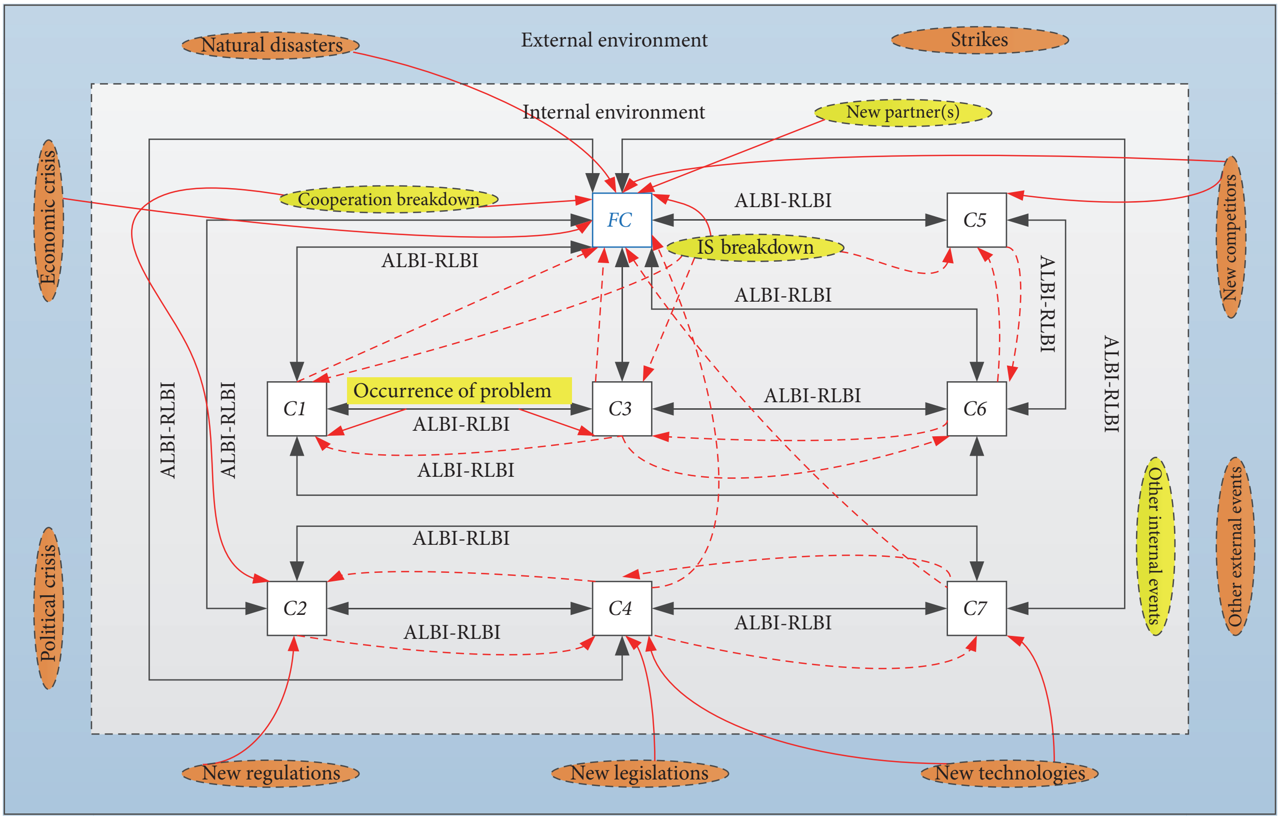
Figure 2 illustrates the theoretical framework that links the construct investigated in this study. Grounded on the theory discussed in Section 3.1 and this section, SCN performance is considered as a multidimensional construct consisting of four dimensions or dependent variables.

4. Model Development

4.1. Rationale for Selecting Agent-Based Simulation. In Section 1, it was stated in the form of a research stance that simulation modeling, more specifically ABS modeling (e.g., [44, 85, 86]), provides an effective set of tools for analyzing the effect of business interoperability on the performance of complex cooperative supply chain networks. The rationale for simulation modeling is that the logical model of the system we are analyzing is not simple enough to be able to use analytical tools to get answer to our research question. Indeed, the high number of dyad relationships usually involved in SCNs, the high number of factors affecting these dyads, the nonlinear interdependencies among them, and the complex network effects that emerge from the interaction of many companies in the SCN make the modeling of such networks too complex for analytical tools. To become analytically tractable, such complexity would require overly simplistic assumptions about the system and companies' behavior, which might bring the validity of the model into question. Although such oversimplifying assumptions could enable us to compute "the exact" effect of business interoperability on the performance of SCNs, they would probably result in an oversimplified model that would not be a valid representation of the system under analysis. We also argue that as the type of systems we are analyzing is pretty complicated, there may not be exact solutions worked out, which is where simulation comes in [110].

The rationale for ABS modeling rests on the nature of the phenomenon that this research seeks to better understand; that is, how different levels of business interoperability in dyad relationships affect the performance of the network of companies that the dyads belong to. The research addresses the network effect resulting from the adoption of different levels of business interoperability in one or more dyad links. The research does not examine how the whole population of companies in the cooperative network reacts to a change in the network environment but investigates how companies belonging to dyads react to that change, individually. Achieving these goals requires a bottom-up approach rather than a top-down approach, which is to say that the dyads that compose the network, the companies that belong to those dyads, and their interactions have to be modeled at the individual level rather than as a whole, as is done in Systems Dynamics (e.g., [111]), for instance. The rationale for this is that if the network is modeled as a whole, it would be more difficult to identify dyads in which the level of business interoperability must be improved and companies in which performance measures must be improved and to understand the network effect. In addition, the need for ABS modeling can be explained by the fact that the phenomenon under analysis involves groups of autonomous and heterogeneous agents that operate in a dynamic environment and our construct of interest (SCN performance) is an emergent outcome of these entities' interactions [44]. We also perceived that as we would need to model the reflexivity, nonlinearity, and emergence aspects of complex cooperative SCNs, traditional discrete simulation tools are not appropriate.

4.2. Description of the Proposed Model. To develop the proposed ABS model, an extended business interoperability framework has been first built to capture the dimensions and subdimensions of business interoperability (see Figure 1). Then, the Axiomatic Design Theory [93, 94] was used to decompose these dimensions and subdimensions into detailed business interoperability functional requirements (FRs) and map them to their respective business interoperability design parameters (DPs)—see details in Cabral [92]. Note that the rationale for using the Axiomatic Design Theory is related to decomposability aspect of CST, discussed in Section 2.3.



FC: focal company
C: company
ALBI: actual levels of business interoperability
RLBI: required levels of business interoperability

Material, information, and financial flows
Direct impact
Indirect impact (network effect)

Figure 4: The theoretical agent-based simulation model.

Drawing upon the principles of the Axiomatic Design Theory, the dimensions and subdimensions of business interoperability have been stated in the form of FRs, which represent the goals or the business interoperability requirements that must be achieved in the design of an interoperable cooperative SCN platform. The dimensions of business interoperability have been stated in the level 1 FR and the subdimensions in the following levels. To satisfy each FR, a DP has been set in a physical domain. DPs are the solutions, mechanisms, methodologies, procedures, and approaches, used to achieve the business interoperability requirements (e.g., electronic data interchange, information systems standards, radio frequency identification, contracts, and specifications). In the scope of this research these DPs are called business interoperability design solutions (BIDSs). Having reached an appropriate level of decomposition, that is, a level where each last level BIDS can be easily comprehensible and implementable, the last level BIDSs have been used as decision variables in the design of the ABS model.

The proposed ABS model consists of a group of companies and a set of dyad links connecting them (see Figure 4). The links are modeled as bidirectional, as information, financial, and material flows in cooperative SCNs typically occur in both directions. Depending on its position or on its role within the cooperative SCN, each company is modeled as an agent with preestablished degree of autonomy to make decisions and characterized by a set of behaviors and attributes—see, for example, [112]. Behaviors are referred to as the way the agents act and react towards their partners, the extent to which they comply with the cooperation rules, the way they react to changes in their business environment, or their willingness to close any emergent interoperability gap. For example, agents may meet the lead-time or not, report the occurrence of a conflict in a timely way or not, provide information on their internal business processes or not, communicate the actual inventory level or not, accept delayed deliveries or not, implement a new information technology/legislation or not, and take initiatives to react to a strike or not. Examples of companies' attributes are production capacity, capacity surplus, safety stock, type of certifications and/or legislation adopted, and so forth.

Based on a preestablished interaction or business rules, the agents interact with each other towards the achievement of the cooperation goals. For example, they negotiate price and conditions, place, and delivery orders, share information on the inventory level, solve conflicts, and so forth. While

Table 1: The proposed business interoperability maturity model.

Maturity level	Description
0-isolated	The BIDS is not implemented and partners are not aware of its importance.
1-initial	The BIDS is not implemented or is implemented but is ad hoc. However, partners are aware of its importance.
2-functional	The BIDS is implemented and imposed by the dominant partner(s) and does not reflect mutual agreements.
3-connectable	The BIDS is implemented reflecting multilateral agreements but not documented.
4-interoperable	The BIDS is well implemented and well documented, reflecting multilateral agreements.

they interact, their interactions and performance are affected by the interoperability gaps that exist in the dyads to which they belong to, the interoperability gaps in the dyads in which they do not belong to, and the interoperability gaps that exist at the network level. As discussed in Section 2.3, cooperative SCNs exhibit interdependence of their components, that is, the agents affect each other in many ways and therefore their behaviors are dependent upon other agents [113] (cited in [114]).

The interoperability gap, for each last level BIDS, may emerge at the dyad or network level. Thus, the BIDSs are modeled as "dyad variables" or as "network variables." A BIDS is modeled as "dyad variable" if it defines the characteristics of a relationship between two companies. Some examples are mechanisms to define cooperation goals, mechanisms to solve conflicts, mechanisms to coordinate collaborative works, mechanisms to provide information on the processing status of the cooperative business processes, and mechanisms to deliver timely, accurate, or complete information. In contrast, a BIDS is modeled as "network variable" if it characterizes the network. Mechanisms to manage the supply-base complexity, mechanisms to manage the customer-base complexity, mechanisms to manage the market uncertainty, and mechanisms to manage external events are some examples.

The approach that drives the analysis of the impact was first proposed in [112] and is explained as follows: considering that the ALBI for a given BIDS is not always the RLBI and vice versa (see Section 3.2), a distance between these two states is proposed to measure the business interoperability gap, that is, how far the ALBI is from the RLBI (see (1)). Consider

$$\text{business interoperability gap} = \text{ALBI} - \text{RLBI}. \quad (1)$$

The assessment of the ALBI and RLBI for each BIDS is grounded on a business interoperability maturity model that has been developed in the ambit of this study. This maturity model, which draws upon earlier literature such as ATHENA [28], Chen et al. [26], Campos et al. [31], and Guédria et al. [22], consists of five maturity levels as shown in Table 1. Note that this maturity model is not linear; that is, the descriptors may differ, depending on the BIDS. For example, some of the BIDSs associated with the dimension of information systems (e.g., speed, accessibility, and user interface) may require a different type of descriptors.

Based on the business interoperability gap, a probability of problem occurrence is estimated, assuming that if there is a gap in a dyad, then there is a *problem-occurrence-chance* probability of problem(s) occurring between the two agents in the dyad. Examples of problems can be inefficient planning and forecasting due to information that is delivered incomplete, inaccurate, or delayed. It is assumed that the greater the business interoperability gap, the higher the probability of problem occurrence. Again, note that the mechanism of the interoperability gap driving behavior (gap versus probability of problem occurrence) is not linear—given the same or different BIDSs, the same gap may have a different impact on different dyads. This is related to the nonlinearity of complex cooperative SCNs, discussed in Section 2.3.

Once an interoperability problem in a dyad occurs (called "problematic dyad"), the model first examines the probability of impact on the two agents in the dyad. The model assumes that the performance of these agents can be directly affected with a *direct-impact-chance* probability. If this probability is greater than or equal to *random-float 1*, the impact is first estimated regarding the agent(s) in the dyad and then spread over the network. Otherwise, there is neither a direct impact nor a network effect. The impact is spread along only established, directed links between two agents. That is, a dyad is only affected if its neighbor(s) has/have been affected. Another rule driving this diffusion is that the nonneighbor dyads have lower chance to be affected than the neighbor ones (given by a variable called *indirect-impact-chance*). If the *indirect-impact-chance* probability is greater than or equal to *random-float 1*, the neighbor agents are indirectly affected, and their performances are updated by assigning the corresponding impact. Note that to assign both direct and indirect impact it is necessary to link each business interoperability gap and the resulting problem to specific performance measures (see Figure 3).

The model can also be used to analyze the impact of external events. The first step is to examine the probability of an external event to occur, given by a variable called *external-event-chance*. An external event occurs when the *external-event-chance* probability is greater than or equal to *random-float 1*. Once an external event occurs, the model first examines the probability of the dyads in the network to be directly affected (given by a variable called *external-event—direct-impact-chance*). An external event affects directly a dyad if the *external-event—direct-impact-chance* probability is greater than or equal to *random-float 1*. This probability is estimated based on the interoperability gaps that exist regarding the BIDSs used to deal with external events. The approach for spreading the effects of these events is similar to the one proposed to spread the effect of an internal interoperability problem.

In the attempt to reduce the probability of occurrence of interoperability problems and make their network more interoperable, agents in cooperative SCNs continuously interact with and react to the network environment in order to create a new version of their network. They analyze their performance, identify dyads where interoperability gaps exist, discuss whether or not to modify their processes in order to close these gaps, and assess whether modifications have improved their performance. Indeed, when an interoperability gap is detected, there is a probability of closing it, and as a result performance might be improved. However, this behavior might be constrained, for instance, by the willingness of agents to modify their internal processes, which may depend on the relationship between investments versus benefits. The model also simulates this decision-making process as well as its impact on performance of the cooperative SCN. To achieve this goal, additional variables and logics are needed to give agents autonomy and intelligence to make informed decisions.

In the ambit of this research, the simple mechanism driving that decision-making process is to outbalance the accumulated investments needed to close an interoperability gap and the potential benefits. The core variables that control the behavior of agents in this process include information regarding relevant business performance, satisfaction level, accumulated investment, potential benefits, willingness to invest, and influencing power an agent has over other agents. For each relevant performance measure, it is assigned an *expected-performance-threshold,* which is later compared with the corresponding *real-performance-score*, given by the plots set in the simulation environment. This comparison, which is supported by a variable called *interoperability-gap-frequency-check*, can be regularly scheduled (e.g., semiannually, quarterly, or annually). If the *real-performance-score* crosses the *expected-performance-threshold*, the *satisfaction-level* regarding the performance measure of interest increases. As a result, the dyad has a *close-interoperability-gap-chance* probability to close the gap. Once the agents in the dyad consider closing the gap, it is necessary to outbalance the *minimum-expected-benefits-threshold* with the *maximum-accumulated-investment-threshold*. If the *minimum-expected-benefits-threshold* crosses the *maximum-accumulated-investment-threshold*, the *willingness-to-close-interoperability-gap* increases.

An interoperability gap is then closed if the *willingness-to-close-interoperability-gap* is greater than or equal to *random-float 1*. Once an interoperability gap is closed, the *real-performance-scores* of time periods t and $t-1$ (t is equal to semester, quarter, year, etc.) are compared, and if the *real-performance-score*$_t$ crosses the *real-performance-score*$_{t-1}$, the agents conclude that the performance has been improved. Otherwise, they conclude that it has not been improved. Depending on the assessment results, their *satisfaction-to-interoperability-gap-closed* becomes the source of positive or negative influence to their neighbors.

5. Case Study: Valorpneu Network

5.1. Case Study Overview. The case study presented in this paper has been conducted in the Valorpneu network and its purpose is to explore and demonstrate the applicability of the proposed ABS model in a specific and real situation, rather than to achieve generalization about the application of the method or the practices [115].

5.2. Characterization of the Network. Valorpneu network is an RL cooperative industrial network that organizes and manages the system of collecting and disposing of used tires in Portugal. The system that supports the activities inherent to this network is called "Integrated System for Management of Used Tires (SGPU)," which started its operation on February 1, 2003. Currently Valorpneu's collection network has 49 collection points, 27 retreaders, 3 recyclers, 4 energy recoveries, and 23 transporters or companies responsible for their subcontracting.

The Valorpneu network is regarded as an important industrial network in Portugal, and its economic, social, and environmental importance is evident. For instance, a study published in 2014 by Valorpneu about management of used tires in Portugal concluded that the system contributes € 78 million to the Portuguese Gross Value Added (GVA) (with reference to 2011) and created 970 direct jobs, 315 indirect jobs, and 698 induced jobs and that, on average, it reduces 1560 kg of CO_2 and 46.5 GJ of energy per ton of used tire managed, per year.

5.3. Characterization of the Participants. In this case study, a sample comprising four companies in the Valorpneu network was chosen. For each company participating in the study, a manager was chosen to be the respondent. The profiles of the four companies and the respondents are provided in Table 2.

5.4. Description of the SGPU Model. The SGPU starts with the introduction of new or second-hand tires into the Portuguese market. Any company producing and/or importing new or second-hand tires—and/or vehicles, aircraft, or equipment that contains new or used tires—needs to celebrate a contract with the managing entity (Valorpneu), allowing the Ecovalue due on the imported tires to be charged. This Ecovalue, which pays for the provision of a service and is charged by tire producers, funds Valorpneu's system.

After reaching the end of their life cycle, tires may be delivered by distributors to collection points spread throughout the country (mainland Portugal and the Autonomous Regions of Madeira and the Azores), at zero cost to the tire holders. To locate the most convenient collection point to deliver tires, there is a Network Map available on the Valorpneu website (http://www.valorpneu.pt/). At collection points, the discharged tires are separated through a well-established sorting process, consisting of five categories (see Table 3), and stored temporarily.

Later, grounded on the inventory level of each of the categories shown in Table 3, tires are routed by Valorpneu from collection points to entities where they are processed (essentially energy recovery and recycling). The management of the information inherent to this complex network is supported by an online information system that enables the different agents within the SGPU to interact, while simultaneously allowing Valorpneu to control and manage

Table 2: Companies' and managers' profile.

	Companies			
	Company 1	Company 2	Company 3	Company 4
Name	Valorpneu	Renascimento	Biogoma	Transportes Bizarro Duarte
Position in the network	Managing Entity	Collection point and transporter	Recycler	Transporter
Sector of activity	Waste management industry	Waste management industry	Waste management industry	Road transport of merchandise
Main service provided	Management of the used tires flows in Portugal	Waste management/logistics provider	Production and commercialization of products derived from used tires	Logistics transport
Years in Valorpneu network business	More than 10 years	More than 10 years (from 2003 to present)	Fewer than 10 years (from 2008)	More than 10 years (from 2003 to present)
Turnover (millions €)	10–20	10–20	Fewer than 10	Fewer than 10
Company size (employees)	Fewer than 50	100–200	Fewer than 50	Fewer than 50
Geographic location	Mainland Portugal (Lisbon)	Mainland Portugal (Loures)	Mainland Portugal (Santarém)	Mainland Portugal (Malveira)
	Interviewees			
	Respondent 1	Respondent 2	Respondent 3	Respondent 4
Job title	Logistics manager	Quality, environment, and security manager	Production manager	Top management
Years in business	More than 10	More than 15	More than 20	More than 10
Years in Valorpneu network business	More than 10	More than 10	Fewer than 10	More than 10

Table 3: Categories of tires at collection points.

Category	Dimension/description
Passenger	Diameter ≤ 0.70 m and width ≤ 0.35 m
Heavy	Diameter ≤ 1.20 m and width ≤ 0.35 m
Industrial	Higher dimensions
Damaged	Heavy tires whose structure is damaged to the point that it is not possible to stand them vertically
Massive	All dimensions of massive tires, excluding bandages

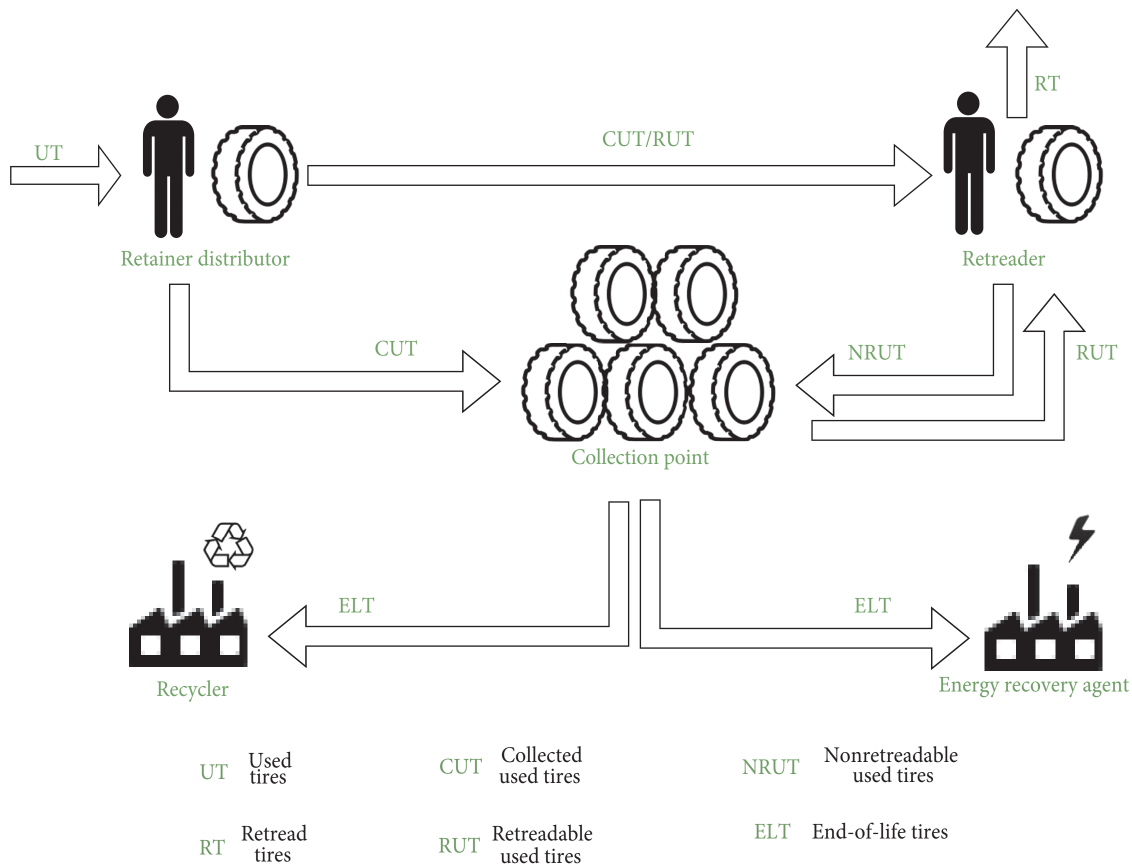


Figure 5: The SGPU working model (source: Valorpneu website).

the whole SGPU. The working model of SGPU is shown in Figure 5.

To help us in the demonstration of the ABS model, a business diagram has been developed to map and systematize the material, information, and financial flows involved in this complex system (see Figure 6).

5.5. Collected Data. Data for this case study were collected primarily through face-to-face interviews. Complementary data were gathered through documents, namely, through the Annual Reports and Newsletter, available on Valorpneu's website. As data were collected through multiple sources, triangulation was used to corroborate the evidence coming from the different sources. These data can be summarized according to two categories: quantitative and qualitative data. Qualitative data are concerned with the characterization of the way that SGPU operators interact (Figure 6), the identification of performance measures and their link to BIDSs and FRs (Figure 3), and the characterization of the ALBI and RLBI (Table 4). Quantitative data are concerned with the SGPU operational performance measures (Table 6) and the numerical quantification of the effect of the BIDSs on the performance measures (Tables 7–10). As the aim is not to provide historical evolution of the SGPU from the beginning of its activity (2003), the time boundaries for data collection were set between 2007 and 2014. The main reason for this is that the annual reports, which contain much of the information needed for this case study, are not available for years prior to 2007.

Note that although the impact of business interoperability has been theoretically linked to the operational, economic, environmental, and social perspectives of business

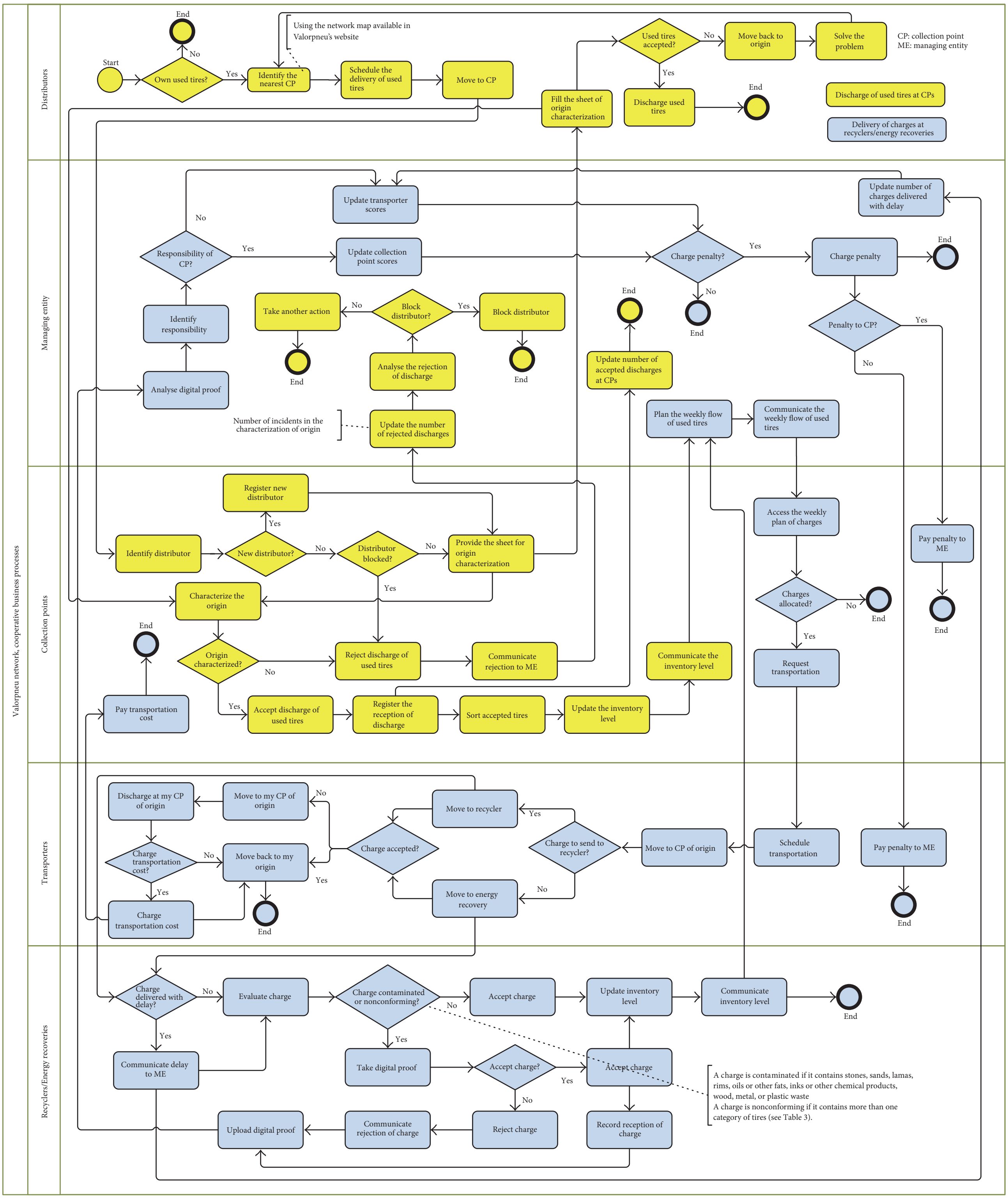


Figure 6: The Valorpneu network business process diagram.

performance (see Figure 2), this case study focuses only on the operational performance of the SGPU, as shown in Figure 3. The rationale for this is that, unlike the operational measures, the other three are more difficult to quantify, in the words of the managers interviewed. Also note that although the developed framework suggests that business interoperability is also multidimensional, many of the dimensions are incompletely or not considered in this case study.

Table 4: ALBI and RLBI for each BIDS.

BIDSs	2007		2008		2009–2014	
	ALBI	RLBI	ALBI	RLBI	ALBI	RLBI
BIDS1.1.1	4	4	4	4	4	4
BIDS1.1.2	0	4	3	4	4	4
BIDS2.1	3	4	4	4	4	4
BIDS2.2	0	4	3	4	4	4

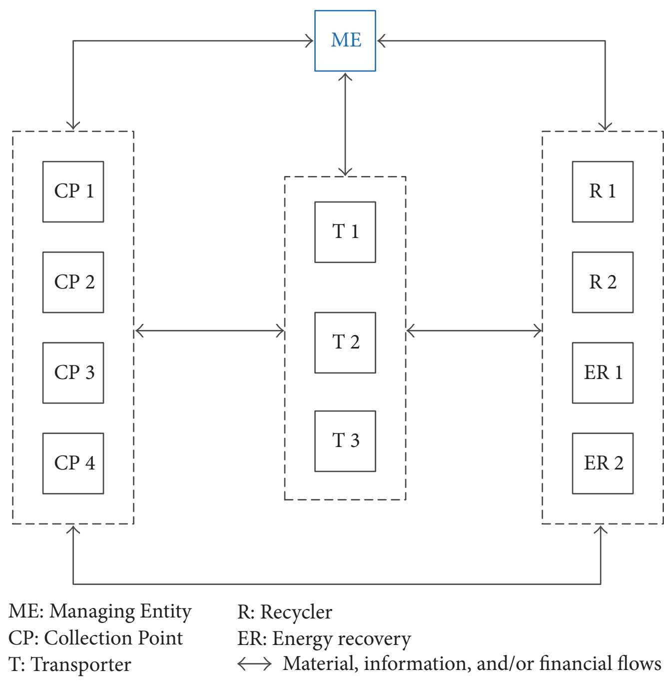


Figure 7: The structure of the considered SGPU.

To be specific, only the BIDSs related to the dimensions "management of external relationships" and "cooperative business processes" are considered. The rationale for this is that, according to the managers interviewed, these two dimensions along with the "information systems" are those with the highest relevance regarding the business interoperability performance of the Valorpneu network. However, the "information systems" dimension is not considered because most of its relevant improvements were achieved prior to the time interval under analysis, that is, prior to 2007. Looking at the extended framework presented in Figure 1, the subdimension considered in the dimension "management of external relationships" is performance evaluation (FR1.1.1 and 1.1.2). In the dimension "cooperative business processes," the subdimensions considered are clarity (clarity in the definition of the system for sorting tires at collection points, FR2.1) and monitoring (FR2.2). The dimension "products and services" is not considered because there is only one product in flow (used tires) and its level of specificity is very low. "Knowledge management" is not modeled because there are no relevant intellectual and property rights (IPR) issues among the SGPU operators. "Employees and work culture" is also not modeled because the interactions among the employees from the different companies within the Valorpneu network are not very frequent. "Business semantics" is not modeled because there are no conflicting terminologies. Last, the dimension business strategy and network details dimension were recognized to be important but not modeled since quantitative data regarding their impact were not available. However, the proposed ABS model is prepared to incorporate constructs related to the ten dimensions of business interoperability and to the four dimensions of performance illustrated in Figure 2.

The values of ALBI and RLBI, in Table 4, were measured through the theoretical business interoperability maturity model provided in Section 4.2. As an example, we use BIDS1.1.2 to show what those values mean (see Table 5).

In 2007, the system for evaluating the quality of the services provided by transporters (BIDS1.1.2) did not exist, corresponding to level zero. In 2008, this system had been implemented but not documented, corresponding to level 3. In 2009, this system was documented, corresponding to level 4. The implications of the improvement of its levels of interoperability are reflected first in the gap between the ALBI and RLBI and then in the performance measures shown in Table 9. For example, in 2007 the gap was equal to minus four and the probability of a charge to be delivered with delay was

Table 5: Measurement of ALBI and RLBI for BIDS1.1.2.

Maturity level	Description
0-isolated	There is no system for evaluating the quality of the service provided by transporters and partners are not aware of its importance.
1-initial	The system for evaluating the quality of the service provided by transporters is not implemented or is implemented but is ad hoc. However, partners are aware of its importance.
2-functional	The system for evaluating the quality of the service provided by transporters is implemented and imposed by the dominant partner(s) and does not reflect mutual agreements.
3-connectable	The system for evaluating the quality of the service provided by transporters is implemented, reflecting multilateral agreements, but not documented.
4-interoperable	The system for evaluating the quality of the service provided by transporters is well implemented and well documented, reflecting multilateral agreements.

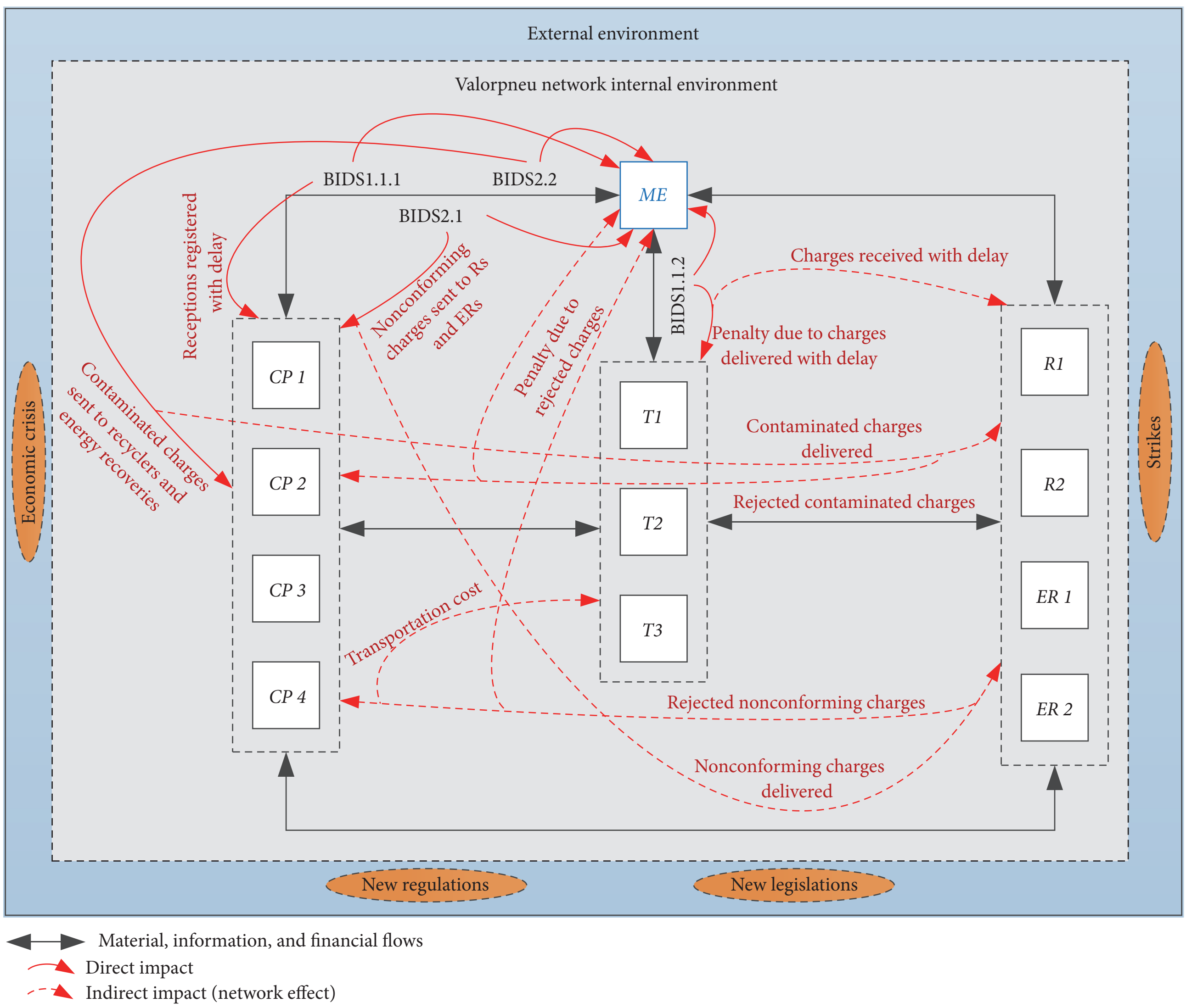


Figure 8: Application of the theoretical agent-based simulation model to the structure of the considered SGPU.

equal to 0.32. In 2008, the gap was equal to minus one and the probability of a charge to be delivered with delay decreased to 0.16. From 2009 to 2014, the gap was equal to zero and the probability of a charge to be delivered with delay was equal to 0.08 in 2009, 0.06 in 2010, 0.02 in 2011, 0.02 in 2013, and 0.012 in 2014.

In addition to the data provided above, some assumptions (A) regarding the performance measures and the impact of

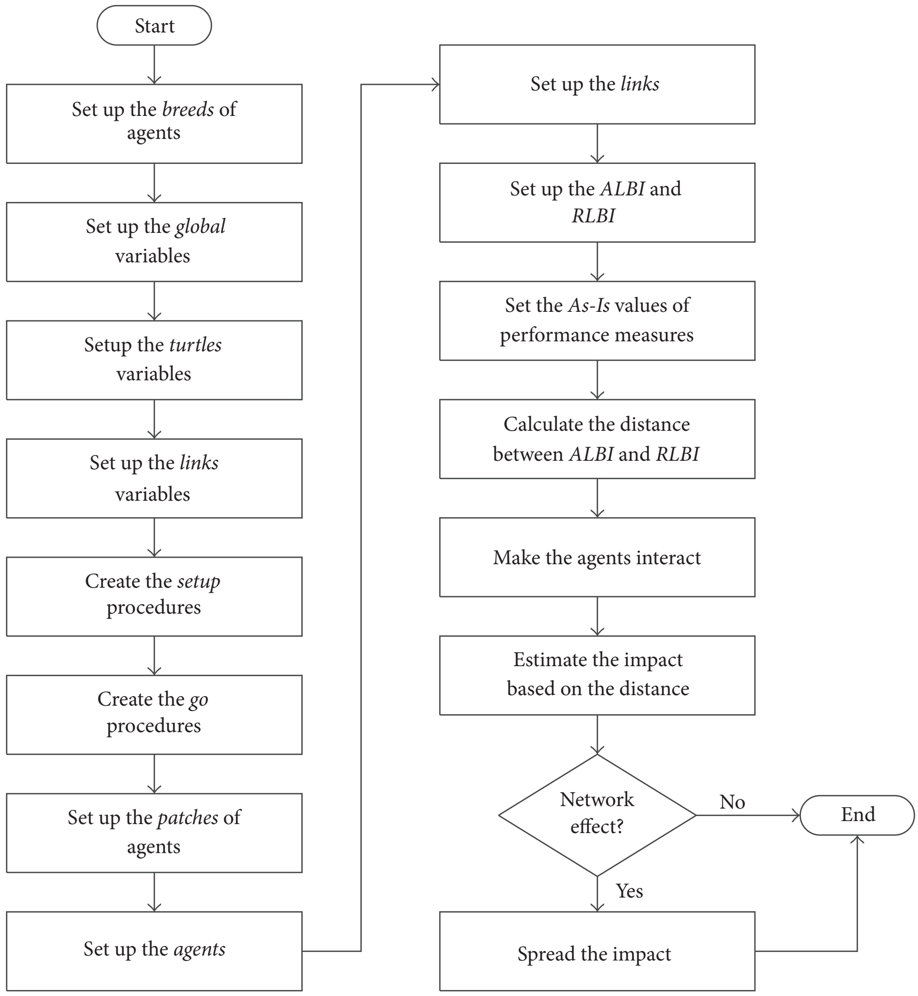


FIGURE 9: Steps to implement the ABS model.

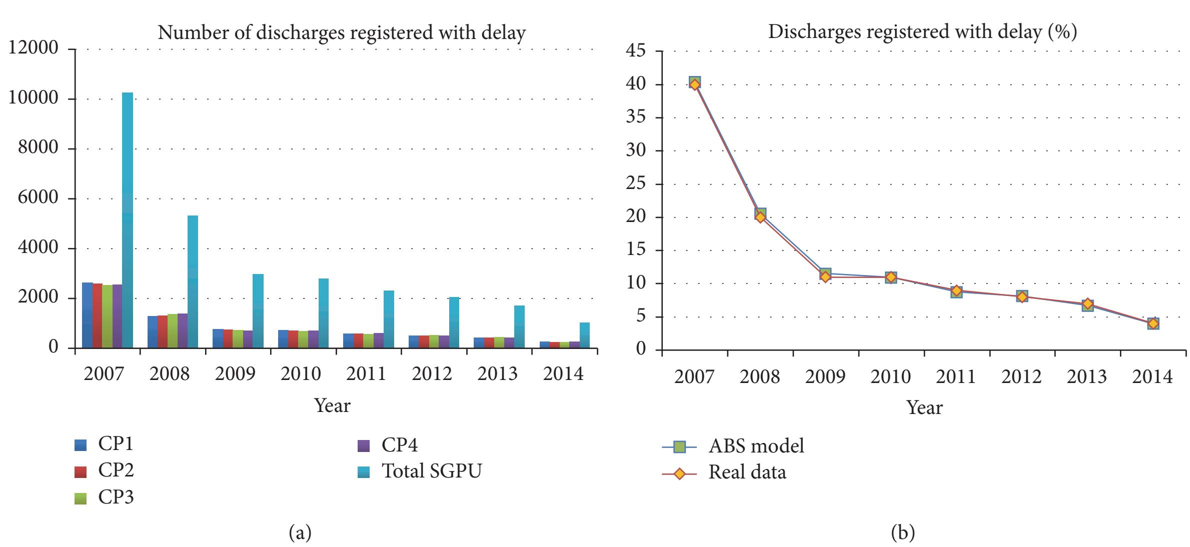


FIGURE 10: Discharges registered with delay.

Table 6: SGPU performance measures (2007–2014).

SGPU performance measures	2007	2008	2009	2010	2011	2012	2013	2014
Used tires sent to recycling (ton)	43,603	48,332	48,039	49,957	47,595	39,203	38,408	43,779
Used tires sent to energy recovering (ton)	22,897	23,504	21,878	25,759	25,144	24,483	26,132	26,621
Total used tires collected and processed by SGPU (ton)	92,321	96,210	89,574	94,373	90,373	78,268	78,695	84,681
Stock at collection points (ton)	10,153	9,487	9,909	10,193	10,531	11,471	11,480	7,354
Operational expenditures, collection points €)	1,562,739	1,766,300	1,790,308	1,919,697	1,837,568	1,596,483	1,610,799	1,756,842
Operational expenditures, transporters (€)	1,864,954	2,130,661	2,031,665	1,987,633	1,898,601	1,653,207	1,648,926	1,778,545
Operational expenditures, recyclers (€)	3,203,910	3,515,209	3,500,083	3,694,921	3,518,372	2,888,800	2,813,461	3,150,101
Operational expenditures, energy recoveries (€)	1,497,220	1,443,804	1,128,443	705,658	624,354	527,928	370,903	306,222
Average expenditures, storage at collection points (€/ton)	21.90	22.69	24.01	24.20	24.56	24.75	24.67	24.69
Average expenditures, transporters (€/ton)	26.14	27.37	27.25	25.06	25.38	25.63	25.26	24.99
Average expenditures, recyclers/energy recoveries (€/ton)	66.23	64.53	62.47	61.82	61.13	57.99	55.44	54.37

Table 7: Impact of the follow-up visits to collection points.

Performance measure(s)	Impact of BIDS2.2, follow-up visits to collection points							
	2007	2008	2009	2010	2011	2012	2013	2014
Contaminated charges sent from collection points to recyclers and energy recoveries (%)	2	1.20	0.37	0.03	0.23	0.54	0.12	0.23

Table 8: Impact of the introduction of the system for evaluating the quality of services provided by collection points.

Performance measure (s)	Impact of BIDS1.1.1, system for evaluating the quality of services provided by collection points							
	2007	2008	2009	2010	2011	2012	2013	2014
Receptions registered with delay (%)	40	20	11	11	9	8	7	4
Number of incidents in the characterization of the origin (per trimester)	64	51	32	23.80	20.30	18.60	17	15.30

Table 9: Impact of the introduction of the system for evaluating the quality of services provided by transporters.

Performance measure (s)	Impact of BIDS1.1.2, system evaluating and the quality of service provided by transporters							
	2007	2008	2009	2010	2011	2012	2013	2014
Charges delivered with delay (%)	32	16	8	6	4	2	2	1.20

Table 10: Impact of the system for sorting used tires at collection points.

Performance measure(s)	Impact of BIDS2.1, system for sorting used tires at collection points							
	2007	2008	2009	2010	2011	2012	2013	2014
Nonconforming charges sent from collection points to recyclers and energy recoveries (%)	2	0.70	0.13	0.03	0.05	0.06	0.08	0.09

Table 11: Assumptions made.

A	Designation	Assumed value
A1	Probability of contaminated charge to be rejected	0.030
A2	Probability of a nonconforming charge to be rejected	0.020
A3	Probability of contaminated and nonconforming charge to be rejected	0.050
A4	Number of discharges per week	$\sim N$ (500; 50)
A5	Inventory cost for each ton of rejected charge (€/ton)	25
A6	Penalty value charged by managing entity to collection points for each rejected charge (€/charge)	$\sim N$ (120; 10)
A7	Washing fee imposed by recyclers or energy recoveries due to contaminated charges (€/charge)	$\sim N$ (25; 2)
A8	Amount of nonconforming tires per each accepted charge (ton/charge)	$\sim N$ (0.13; 0.015)
A9	Amount of contaminated tires per each accepted charge (ton/charge)	$\sim N$ (0.15; 0.025)
A10	Penalty value charged by managing entity to transporters for each charge delivered with delay (€/charge)	$\sim N$ (25; 2)
A11	Weight of each charge to recyclers and energy recoveries (ton/charge)	$\sim N$ (12.5; 1.2)
A12	Number of working weeks per year	51

business interoperability were made in order to overcome the lack of data (see Table 11). Note that these assumptions were made and validated during the interviews with the manager of the managing entity (Valorpneu).

5.6. Demonstration of the Proposed Model. One of the issues when analyzing SCNs is the need to set the boundaries of the study object, that is, what will be investigated and what will not be. In the context of this case study, retreaders and shredders are not included in the application of the ABS model because according to the managing entity manager, they are not relevant in terms of interaction with the other SGPU operators. Although only one company per each type of agent participated in the study, the ABS model is demonstrated with the agents illustrated in Figure 7. The rationale behind this is to have more agents in order to better understand the network effect.

As can be seen in Figure 4, the ABS model is generic and incorporates a number of internal and external variables. To show how the constructs defined in Figure 3 have been incorporated in this new scenario, a new version of Figure 4, more simple, has been created—see Figure 8.

To more easily understand how the ABS model is implemented, a detailed simulation process flowchart is provided in Figure 9.

As shown in Figure 9, the first step in implementing the ABS model is to set the *breeds* of agents. *Breeds* are the type of agents involved in the system being modeled. In this study, the system being modeled consists of the five types of agents shown in Figure 7.

Step two consists of defining the *global* variables, that is, those that characterize the network as a whole (e.g., number of collection points, number of transporters, probability of strike, and number of loads a week). Step three is to set up the *turtles*' variables. Turtles here are the agents in the system, that is, the breeds defined previously. These types of variables can be *turtles*' variables or *breeds*' variables. The first can be accessed by any turtle (e.g., type of information system used, time spent in reworking information), while the second can only be accessed by turtles of the same *breed*. Examples of *breeds*' variables, for collection points, are storage capacity, reference stock, and amount of collected tires per day.

The fourth step is to set the *links*' variables, which are those that characterize each dyad relationship. In the scope of this study, these variables are the ALBI, the RLBI, and the gap between ALBI and RLBI. Step five is to create the *setup* and *go* procedures. These are buttons created in the interface to allow the user to initialize *(setup)* and start *(go)* the simulation. Following this, the *patches* of agents are created. Patches are the virtual world where the agents operate and interact.

The next step is to create the agents, their position (can be random or fixed), and their *shape* (factory, truck, person, computer, etc.). Once agents are created, it is necessary to set the links among them. In this work, directed links have been established. The next step is to set the corresponding values of the *links*' variables, which are the ALBI and RLBI measured through the maturity model (see Tables 4 and 5), and the performance measures being analyzed. Grounded on these values, the business interoperability gap is calculated using (1).

The last three steps consist of making the agents interact, estimating, and spreading the impact of business interoperability on performance. To make the agents interact, the interaction and decision rules in Figure 6 have been used. For each type of interaction (e.g., delivery of tires at recyclers and/or energy recoveries) it is necessary to identify the BIDS(s) that affect(s) the interaction and relate the BIDS(s) to performance measures (see Figure 3). For example, in the process of delivering tires to recyclers and/or energy recoveries, upon the arrival of the truck the recovery agent receiving the load should evaluate whether it is contaminated, in conformity, or delayed, and decide whether the charge is accepted or not. The probability of a charge to be delivered with delay depends on the gap between the ALBI and RBI for BIDS1.1.2 (measured using data provided in Table 4), and the performance measure related to this process is "percentage of charges delivered with delay" (see Table 9). Similarly, in Table 10, it was set that the probability of a nonconforming charge sent from collection points to recyclers and energy recoveries is dependent on the BIDS2.1. To model whether a charge is contaminated or not, the following condition has been used:

if (random-float 1) < probability-of-a-charge-to-be-contaminated

set contaminated-charge true

set number-of-contaminated-charges number-of-contaminated-charges + 1

else

set contaminated-charge false

end

The approach used to model whether a charge is not in conformity or delivered with delay is the same as shown above. In the event that a charge is contaminated, nonconforming, or delivered with delay, the probability of rejection, as well as the potential impact, is modeled on the basis of the assumptions made in Table 11. For example, when a charge is contaminated, the decision on its rejection is dependent on the A1—probability of a contaminated charge to be rejected. For this purpose, the following condition has been used:

if (random-float) 1 < probability-of-a-contaminated-charge-to-be-rejected

reject charge

set number-of-rejected-charges number-of-rejected-charges + 1

else

accept charge

set number-of-accepted-charges number-of-accepted-charges + 1

end

Once a charge is rejected, the impact is then spread to the agents that to some extent are involved in the process of delivering the charge. The assumptions used to estimate the impact of this scenario are A5, A6, and A7. For example, the penalty value charged by the managing entity to collection points due to each rejected charge is assumed to be normally distributed, with mean and variance equal to 120 and 10, respectively. The transportation cost charged by transporters to the collection point responsible for the rejected charge is the round trip cost of the value paid by the managing entity to transporters (€/ton—see Table 6).

5.7. Simulation Experiment and Results. One of the issues that is not yet consensual regarding the execution of ABS models is the number of replications that are needed. For example, North and Macal [116] consider the need for designing sets of

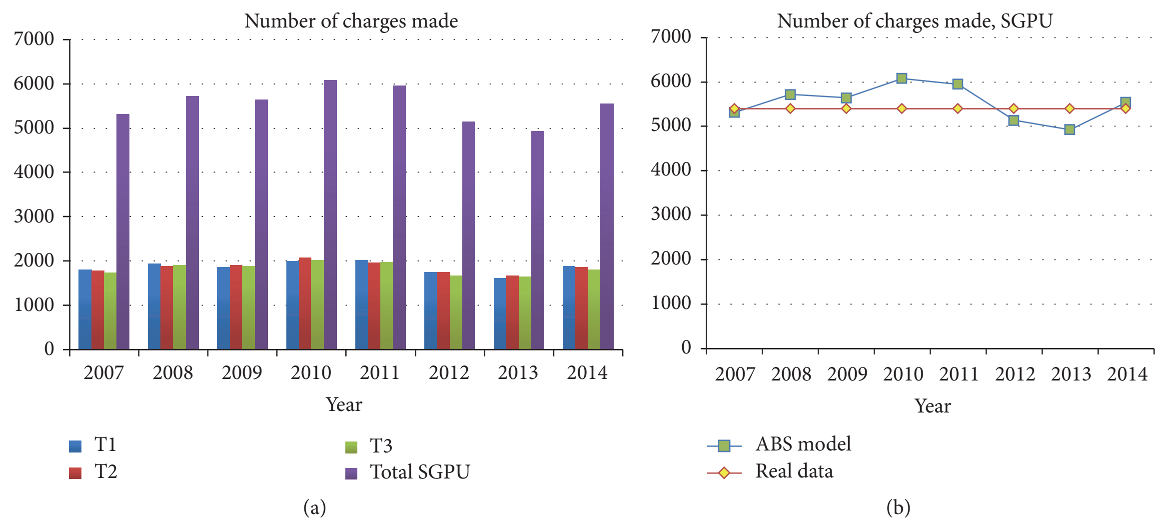


Figure 11: Number of charges made.

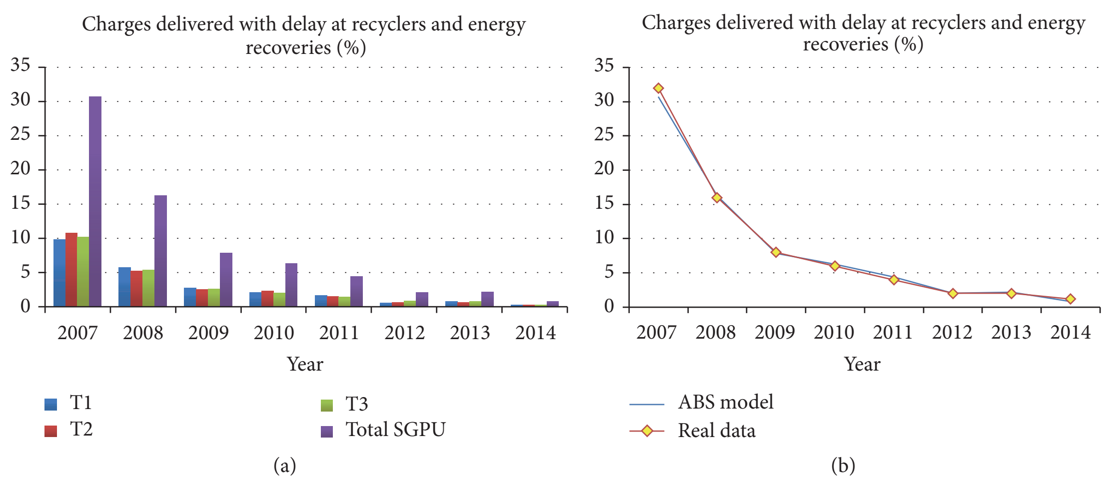


Figure 12: Percentage of charges delivered with delay.

many simulation runs, many more than is the usual practice for standard simulation models, to fully understand system and agent behaviors. However, they do not specify a concrete number. In this research, the model has been replicated 100 times, although, for example, Rand and Rust [44] suggest that 30 runs are acceptable. NetLogo 5.0.5 [117] was used to simulate the model, which was run on a weekly basis. The most relevant simulation outputs are reported in Figures 10–17. First, Figure 10 summarizes the simulation outputs related to the process of discharging tires at collection points.

Second, Figures 11–14 show the simulation outputs for transporters regarding the process of delivering charges at recyclers and energy recoveries.

Third, Figures 15–17 summarize the simulation outputs for collection points regarding the process of delivering charges at recyclers and energy recoveries.

The simulation outputs for collection points due to contaminated, nonconforming, and rejected charges at recyclers and energy recoveries are provided in Figures 18–21.

Before analyzing the case (see the next section), it is important to compare the results from the ABS model to the system output data in order to ensure that valid conclusions are drawn. In other words, it is important to ensure that the model simulated is a reasonable representation of the real system—model validation. An analysis of Figures 10, 12, 16, and 17 suggests that the model behaves as the same as the real system. However, statistical validity is needed to support this assumption. Statistical techniques, such as Z-test and t-test to compare the means and F-test to compare the variances, are usually applied for this purpose. A fundamental requirement to apply these tests is the normality of the two data sets. However, in this case study, the output performance measures from the model and the real system are nonnormal. In addition, it is not reasonable to assume that the two data sets are normally distributed because the sample size is small (8 years). Therefore, a nonparametric test is applied to verify, for a given significance level, whether the medians of populations of the model output data and the system output data are

Table 12: Decision values for the Mann–Whitney–Wilcoxon test.

Parameter	Test parameters Designation	Receptions registered with delay (%)	Charges delivered with delay (%)
$U_{\text{Real System}}$	Rank sum test of the real system	38	20
$U_{\text{Simulation Model}}$	Rank sum test of the simulation model	37	20
U	Rank sum test	37	20
$\overline{n}$	Mean of U	32	32
S	Standard deviation of U	10,99	10,99
Z_{test}	Computed test statistic Z	−0,32	−1,26
α	Level of significance	5%	5%
	$Z_{0,975}$	1,96	1,96
	Decision rule	$\lvert Z\rvert = 0{,}32 < Z_{0,975}$	$\lvert Z\rvert = 1{,}26 < Z_{0,975}$
	Decision	Do not reject the null hypothesis	Do not reject the null hypothesis

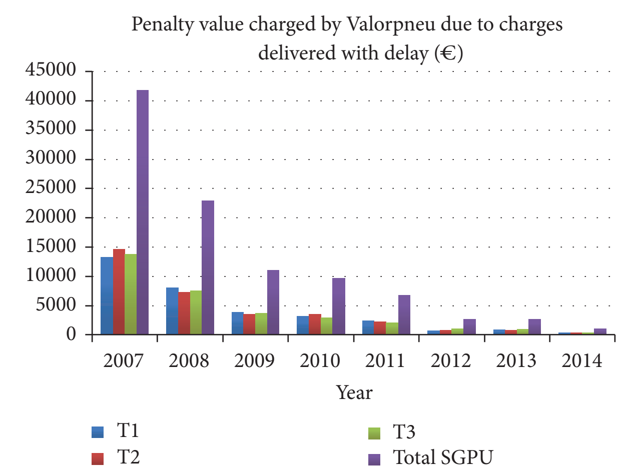


Figure 13: Penalty value charged by Valorpneu due to charges delivered with delay.

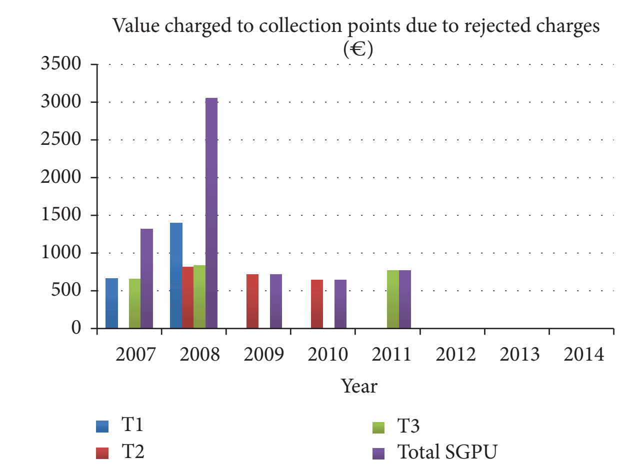


Figure 14: Value charged to collection points due to rejected charges.

significantly different. The statistical technique applied is the Mann–Whitney–Wilcoxon test (for details on how to apply this test, see, e.g., [118]), and the performance measures evaluated are "receptions registered with delay" and "charges delivered with delay." Table 12 shows the computed values for the Mann–Whitney–Wilcoxon test and the conclusions drawn.

As can be seen in Table 12, the Z_{test} values for the two performance measures evaluated are between −1,96 and 1,96. Thus, for a significance level of 5%, there is no evidence to reject the null hypothesis, suggesting that there is no statistically significant difference between the model output data and the system output data. This suggests that the simulated model behaves the same as the real system; that is, it is valid.

5.8. Analysis of the Case. According to one of the managers interviewed, Valorpneu network is known as one of the industrial networks with the best business interoperability performance in Portugal. Taking a look at the simulation outputs, it is possible to state that indeed the implementation of appropriate levels of business interoperability has helped to reduce several non-value-adding processes and consequently improve the operational performance of the Valorpneu network. For example, the existence of a well-defined system for sorting used tires at collection points—defined in the document "Collection Point: Rules and Procedures" (BIDS2.1)—has helped to maintain a low number of nonconforming charges sent to recyclers and/or energy recoveries. This document was created in 2007, and therefore its level of business interoperability was considered to be 3 in that year and 4 from 2008 to 2014. As can be seen in Figure 17, the effect of this BIDS is evident. From the 5400 charges performed every year (see Figure 11), fewer than 2% of nonconforming charges are sent from collection points to recyclers and energy recoveries. In 2007, the number of nonconforming charges was around 2%. Since 2008, this number has decreased year after year. For example, in 2008 it was around 0.7% and in 2014 around 0.07%.

Despite the significance of the impacts discussed above, the most important improvements achieved in the last seven years in the Valorpneu network are related to the introduction of the BIDS1.1.1 and BIDS1.2.2. The main impacts of these systems are in the percentage of charges delivered with

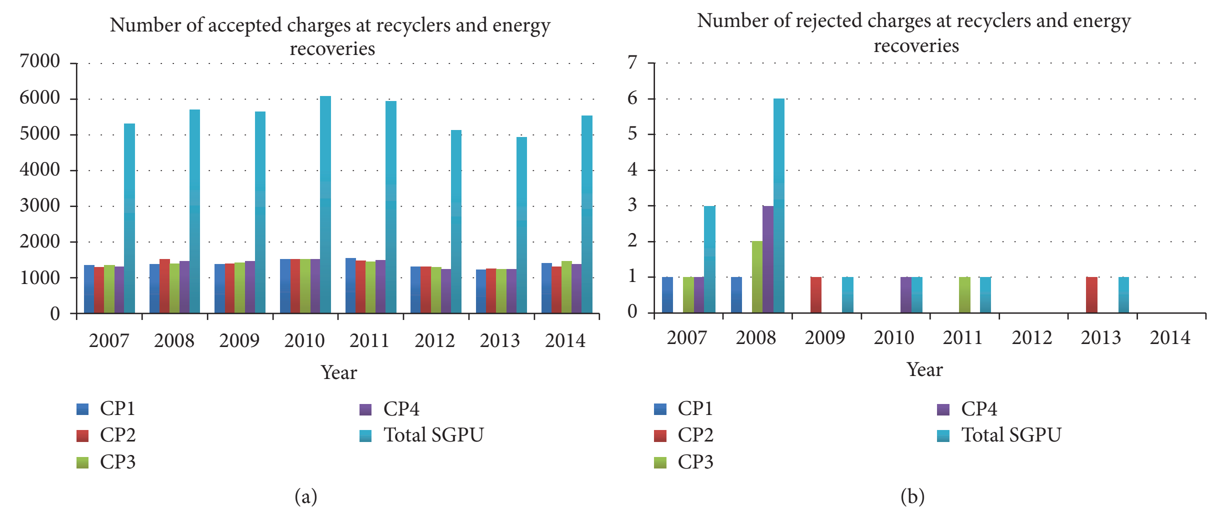


Figure 15: Number of accepted/rejected charges-recyclers and energy recoveries.

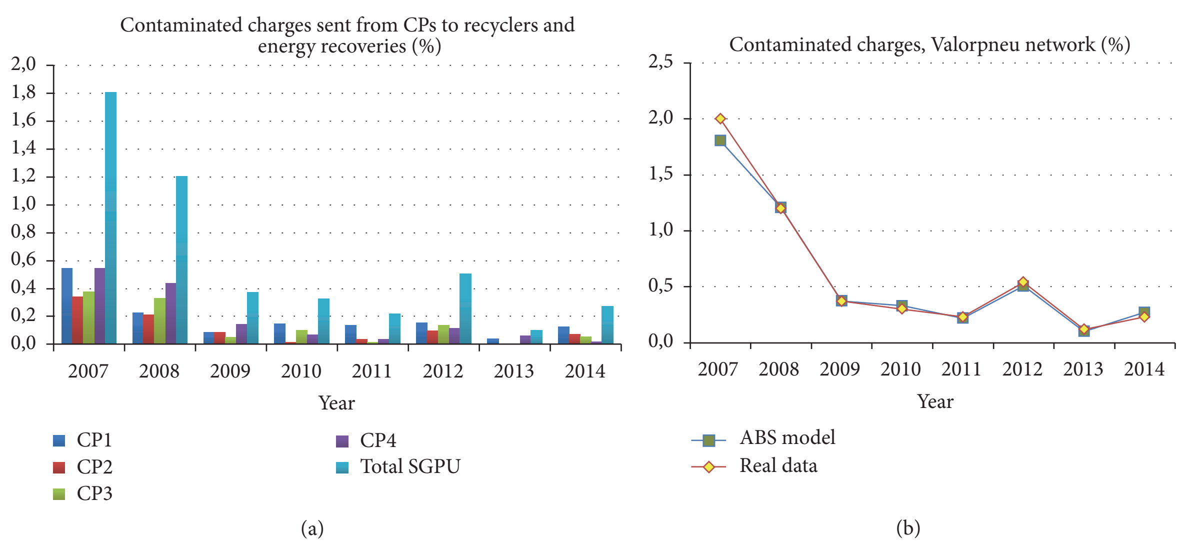


Figure 16: Percentage of contaminated charges sent from collection points to recyclers and energy recoveries.

delay (related to BIDS1.1.2) and the percentage of receptions registered with delay (related to BIDS1.1.1). As can be seen in Figure 12, the percentage of charges delivered with delay fell from 30.71% in 2007 to 0.83% in 2014. The reason behind the high percentage of delays in 2007 is that at that time BIDS1.1.2 did not exist, corresponding to the level zero. With the introduction of this system in 2008, which increased the level of business interoperability to 3, there was a considerable reduction from 30.71% to 16.22%, a reduction of 47.18% (with reference to 2007). However, the system reached the maximum level of maturity (level 4) only in 2009. As a result, a reduction of 53.82% (16.22% in 2008 and 7.49% in 2009) was achieved in 2009. With the maturation of this BIDS1.1.2 in 2009, the amplitude of its impact stabilized and in 2014 the corresponding value was about 0.83%.

Regarding the registration of receptions, Figure 10 shows that the introduction of BIDS1.1.1 has also helped to significantly reduce the percentage of receptions registered with delay. Similarly to the metric number of charges delivered with delay, in the year of the introduction of BIDS1.1.2 (2008), there was a substantial reduction of 49.17% (40.37% in 2007 to 20.52% in 2008) in the percentage of receptions registered with delay. In the same way, in the second year of maturation (2009) the reduction was around 50% with reference to 2008. After 2009, the amplitude of its impact stabilized, as we see with the metric number of charges delivered with delay.

In addition to these impacts, the introduction of BIDS1.1.1 has also helped to reduce the number of incidents in the characterization of origins at collection points. For example, in 2009 the average number of incidents per trimester was around 31. In 2014, this value had fallen to 16, representing a reduction of 48.39% (with reference to 2009). In 2007, before the introduction of BIDS1.1.1, the average number of incidents was estimated to be around 69 per trimester.

Regarding the number of contaminated charges (related to BIDS2.2), the impact is also considerable. Despite the high

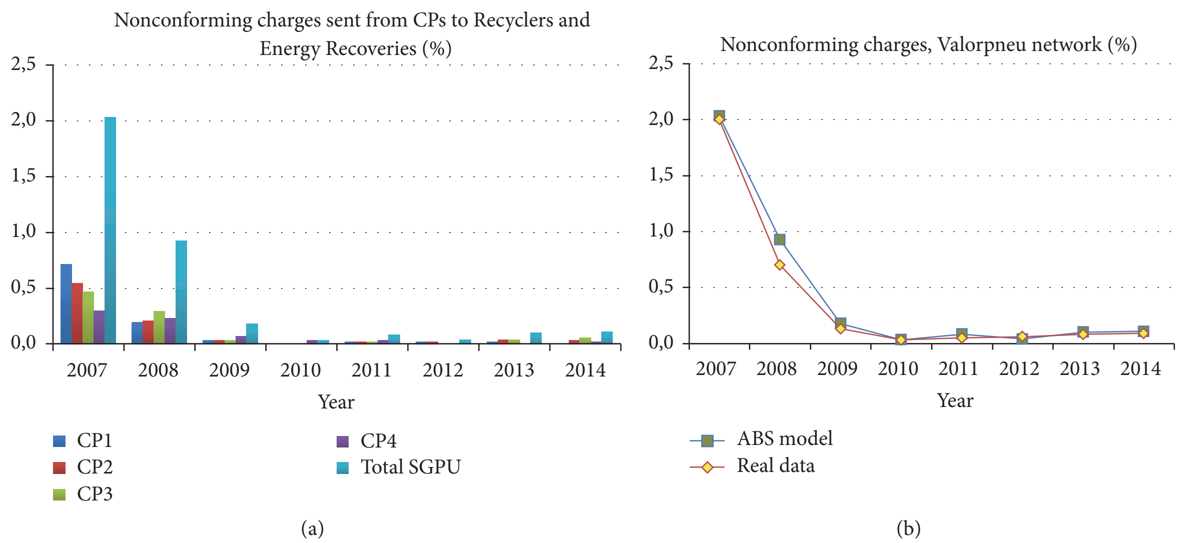


FIGURE 17: Percentage of nonconforming charges sent from collection points to recyclers and energy recoveries.

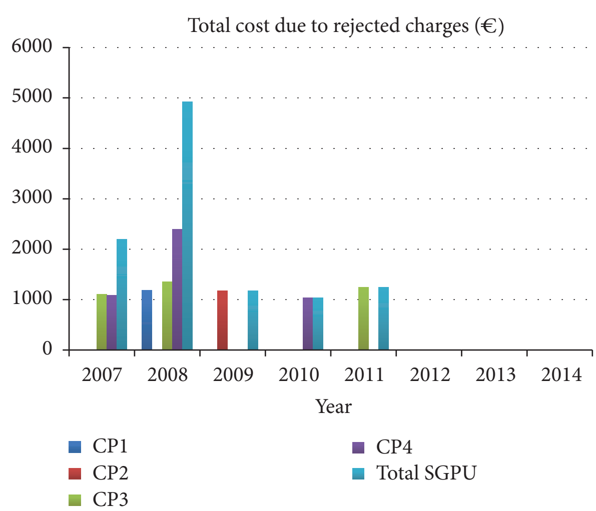


FIGURE 18: Total cost for CPs due to rejected charges.

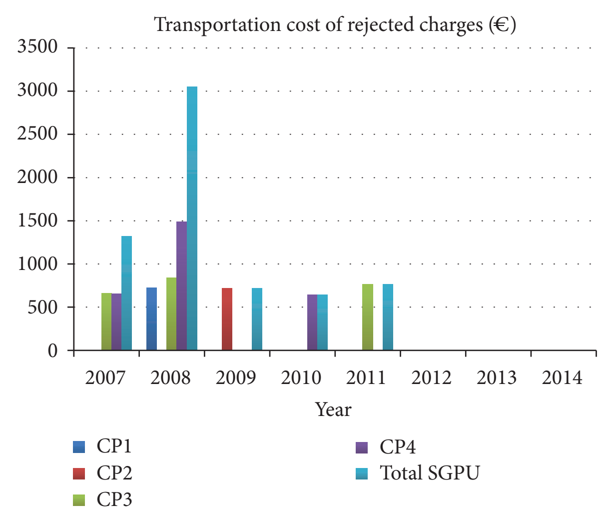


FIGURE 19: Transportation cost paid to transporters due to rejected charges.

number of loads carried out every year in the scope of SGPU, the percentage of contaminated charges was around 0.27% in 2014. From Figure 16, we see that this value fell sharply after 2008 (69 in 2008 to 15 in 2014). The reason for improvement is that since 2008 the managing entity intensified the follow-up visits to collection points.

The findings discussed here support both Hypotheses 1 and 2. First, the gap between ALBI and RLBI on BIDSs related to the dimensions "management of external relationships" and "cooperative business processes" affected the operational performance of the SGPU operators, as predicted in Hypothesis 1. Second, the gap between ALBI and RLBI in dyads affected the performance of companies in other dyads. The implementation of a system to evaluate the performance of transporters affected the performance of collection points, recyclers, and energy recoveries, thereby supporting Hypothesis 2.

6. Conclusions

6.1. Conclusions on the Research Question. This paper proposed an agent-based model to simulate the interactions among cooperative networked companies and analyzed how business interoperability affects their interactions and performance. The paper addressed a research question defined on the basis of an important gap in business interoperability and operations management (OM) literature: existing works do not explain how to analyze the effect of business interoperability on the performance of networked organizations, taking into account the network effect.

With regard to the research question, the findings of this study suggest that indeed ABS modeling provides a set of effective tools to analyze the effect of business interoperability

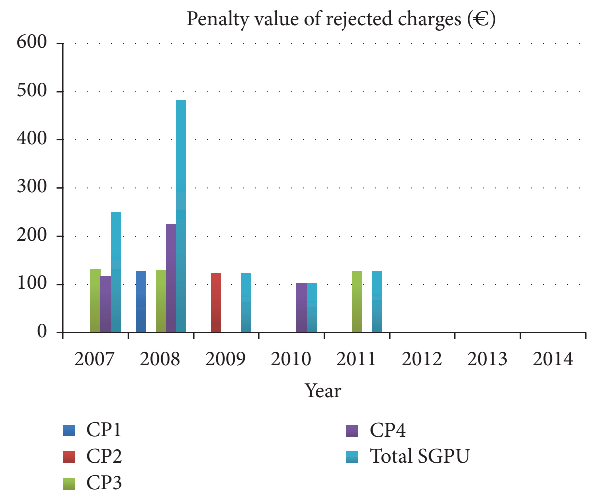


FIGURE 20: Penalty value paid to transporters due to rejected charges.

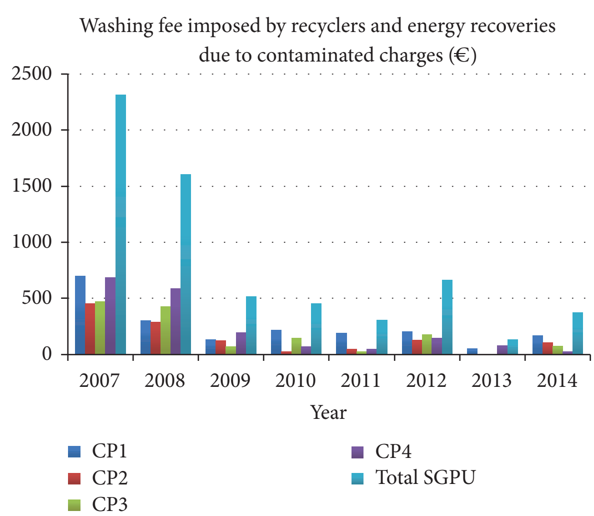


FIGURE 21: Washing fee imposed by recyclers and energy recoveries due to contaminated charges.

on the performance of cooperative SCNs, as it enabled the researcher to

(1) model the interaction among the SGPU operators;

(2) model the way that each BIDS can affect companies' interaction by linking each interaction process to specific BIDSs;

(3) model the probability of occurrence of business interoperability problems based on the gap between the ALBI and RLBI for each BIDS;

(4) model the occurrence of business interoperability problems when companies interact and spread the impact of such problems to other members of the network;

(5) estimate the effect of the business interoperability problems, first on the performance of the agents belonging to the relationship(s) in which the problem occurred and then on the performance of the other companies.

Summarizing, the main research gap (the network effect) can be effectively captured using the proposed ABS model. For example, in the case study presented here, a situation was modeled in which a charge sent by a collection point to a recycler or an energy recovery is rejected due to contamination and/or nonconformity. The impact of this rejection was first assigned to the collection point responsible for sending the rejected charge and then spread to transporters and the managing entity. The transporter benefits from the transportation cost paid by the collection point (round trip transportation cost) and the managing entity charges a penalty to the collection point due to the rejected charge. This situation could have a considerable effect on the performance of the recycler or energy recovery that rejected the charge if its current inventory level is not enough to ensure that its production is not interrupted. This evidence from the data collected supports Hypotheses 1 and 2.

6.2. Theoretical Implications. This paper proposes a model that can be used by researchers from different areas such as business interoperability, SCM, and OM in general to simulate how organizations interact in business networks and analyze how business interoperability can affect their performance. In terms of relevance to theory, this is the first time that the network effect is taken into account in the analysis of the effect of business interoperability on the performance of SCNs. In short, the main difference regarding the existing studies is that this research addresses the network effect. Testing the effect of the levels of business interoperability on performance is also a novelty and contributes to filling gaps in the current literature. Another relevant contribution of this research is that, unlike earlier works, it explores organizational issues, namely, those of the dimension "management of external relationships." This is in line with Hypothesis 1 and reinforces our assumption that business interoperability is not a technological issue only. The extended business interoperability framework shown in Figure 1 also adds to the literature as it incorporates several elements that have never been captured before (e.g., information quality). It can also be used in future empirical research on the effect of business interoperability on the performance of other business networks such as value network and the network of systems within a company. Also, it can be used to design configurations of interoperable business network platforms—see the example in Cabral [92].

6.3. Managerial Implications. With regard to the practical contribution, the theoretical framework and the ABS model proposed in this research are intended to support SCN managers in decision-making processes regarding the business relationships their companies have with their business partners. In other words, it is intended to provide a model and a framework that can guide them on how to analyze the effect of business interoperability on the performance of the networks in which their companies operate. In a more detailed way, the model seeks to help managers to

(1) better understand the complex nature of the business networks in which their companies operate and identify points where improvements in terms of business interoperability and operational performance can be achieved;

(2) better understand how the business relationships between their companies and their partners, and the whole network in which they operate, evolve over time;

(3) make informed decisions on the mechanisms of business interoperability that can be used by their companies and their partners;

(4) better analyze the impact of the implementation of a given BIDS;

(5) set the appropriate level of business interoperability for each BIDS, thereby avoiding unnecessary investments;

(6) predict the occurrence of business interoperability problems, not only between their companies and their partners but also between their partners and other elements of the network, and implement preventive actions rather than mitigation plans;

(7) better understand how internal events such as cooperation breakdown, entrance of new partners, and information system breakdown can impact the performance of their companies;

(8) better understand how external events, such as economic crisis, strikes, introduction of new technologies and/or legislations, and new competitors, can impact the performance of the network of companies in which they operate;

(9) identify the dyad(s) in which the levels of business interoperability are inappropriate and make informed decisions on behalf of the whole network.

6.4. Limitations and Future Research. This research is subject to a number of limitations. First, only one case study was conducted, which implies that conclusions cannot be generalized. Second, the data collected were not enough to fully explain the network effect, as in most cases the managers interviewed recognized that the network effect is a real "phenomenon" in the Valorpneu network but were unable to quantify its impact. Third, although the theoretical framework suggests that interoperability and performance are both multidimensional, the performance is reduced to two dimensions (economic and operational) and only some elements related to the dimensions "management of external relationships" and "cooperative business processes" have been considered in the demonstration of the ABS model.

Taking into account these limitations, there are many ways to extend this work in the future. First, more empirical data need to be collected in order to better explain the network effect and the link between the dimensions of business interoperability and performance. Second, the proposed ABS model must be applied to other business network contexts (e.g., automotive and aircraft industries) in order to compare the outcomes with those reported here. Also, more case studies need to be carried out in order to better decide on the appropriateness of ABS modeling to analyze the effect of business interoperability on the performance of companies, in a context of complex cooperative SCNs.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Research Article

Discrete Switched Model and Fuzzy Robust Control of Dynamic Supply Chain Network

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Supply chain network is more complex and dynamic under the uncertain demand and the lead time. Robustness is a key index of the stable operation for the supply chain network. We investigate a fuzzy robust strategy to realize the robust operation of the supply chain network with the production lead times and the ordering lead times under the uncertain customer demand. A discrete switched model of the dynamic supply chain network with the lead times and the uncertain customer demand is established based on T-S fuzzy systems. Then a fuzzy switched strategy is proposed to control the switching actions among subsystems. Furthermore, by introducing the inhibition rate γ, a fuzzy control strategy for the dynamic supply chain network is put forward to suppress the impacts of the lead times and the uncertain customer demand on the operation of the dynamic supply chain network. The fuzzy robust strategy composed of the fuzzy switched strategy and the fuzzy control strategy can guarantee the robust operation of the supply chain network at low cost. Finally, the simulation researches show the advantage of the proposed fuzzy robust strategy through the comparisons with the common robust strategy.

1. Introduction

As an important management mode, supply chain management is a key factor to enhance the performance of firms in the global marketplace. With the fast changes of global economy and the increasing pressure of market competition, supply chain system has become a complex dynamic network system. The complexity of the supply chain network includes two aspects: on the one hand, the supply chain network consists of numerous economic subjects (such as manufacturers, distributors, and dealers), and there exists a variety of demand and supply relationships among the economic subjects, which form the structural complexity of the supply chain network; on the other hand, the uncertain demand and the lead time in the supply chain network cause the demand forecast to be more difficult, which forms the operational complexity of the supply chain network. For the structural complexity of the supply chain network, there are many research results about mathematical optimization strategies [1–7] and control strategies [8–10].

However, the uncertain demand and the lead time make the supply chain network more dynamic, which will make it more difficult for the supply chain network to achieve smooth operation. For the robustly stable supply chain network with the uncertain demand and the lead time, the system variables (such as inventory) can return to the normal states within a certain amount of time. Conversely, the unstable system will encounter the inventory backlog or serious out of stock phenomena, which will lead to the high operation cost of the system. For example, the operation cost of the supply chain under chaotic state will be more than 500 times higher than that under stable state [11]. Therefore, how to cope with the impacts of the uncertain demand and the lead time on the supply chain network and realize the robustly stable operation of the supply chain network with low cost has received much attention.

For the supply chain network with the uncertain demand, using a scenario-based approach, Almansoori and Shah [12] presented key strategic and operational decisions on the future hydrogen supply chain network with uncertainty arising from long-term variation in hydrogen demand. Khatami et al. [13] applied Benders' decomposition to solve the stochastic mixed-integer model to optimize the closed-loop supply chain network with the uncertainties of products demand and returned products. For the stochastic demands of a multistage and multiperiod supply chain network, Govindan and Fattahi [14] applied a Latin hypercube sampling method to obtain risk-averse and robust solutions. Utilizing the combination of sample average approximation and Latin hypercube sampling methods, Hamta et al. [15] addressed the optimization of strategic and tactical decisions in the supply chain network design under demand uncertainty. Using a simulation-optimization approach to capture the randomness of the uncertain parameters, Salem and Haouari [16] investigated a three-echelon stochastic supply chain network design problem under the uncertain supply and the demand to minimize the total expected cost. Hamta et al. [17] proposed a scenario generation algorithm to deal with demand uncertainty for the supply chain network design considering assembly line balancing. Constructing a three-stage hybrid robust/stochastic program model, Haddadisakht and Ryan [18] optimized the design of a closed-loop supply chain network with uncertainty in demands for both new and returned products.

There are few literature sources on the supply chain network with the lead time. Eskigun et al. [19] modeled the relationship between the lead times and the volume of flow through the nodes of an automotive supply chain network. For companies that implement a Make-to-Order production system in a global supply chain network, Xiao [20] proposed a theory named the Key-Part Based Lead Time Management to reduce nonvalue added waste. In order to deal with the approximate optimal inventory control problem of the supply chain networks with lead time, introducing a sensitivity parameter, Han et al. [21] transformed the original optimal problem into a sequence of two-point boundary value problems without time-delay term.

There are fewer literature sources on the supply chain network with the uncertain demand and the lead time. Li and Liu [22] stated a robust control method to minimize the negative effect of uncertainties in demand, production process, supply chain network structure, inventory policy implementation, and vendor order placement lead time delays. Fattahi et al. [23] exploited the mitigation and contingency strategies for a multiperiod supply chain network with stochastic demands and delivery lead times.

Moreover, the management and control of the inventory is one of the most important subjects in the supply chain network. Because the inventory levels of firms often change, firms will carry out different strategies of production or ordering for the different inventory levels to reduce cost [24]. However, all of the literature sources mentioned above did not consider the different production strategies and ordering strategies for the different inventory levels.

In this article, a dynamic fuzzy model of the supply chain network with the uncertain demand and the lead times is constructed, which involves not only manufacturers' safety inventories and expected inventories, but also distributors' safety inventories and expected inventories. Then, based on the different production strategies and ordering strategies for the different inventory levels, we present a fuzzy switched strategy to suppress the fluctuations of the system variables in switching processes. What is more, we propose a fuzzy control strategy to make the fuzzy supply chain network robustly asymptotically stable in the presence of the lead times and the uncertain customer demand. Finally, simulation experiments are executed to study the impacts of the lead times, the uncertain customer demand, and the fluctuation of the switching processes among subsystems on the supply chain network under the common robust strategy and the proposed fuzzy robust strategy composed of the fuzzy switched strategy and the fuzzy control strategy, respectively.

The rest of this article is organized as follows: In Section 2, a basic dynamic supply chain network system is constructed and then the constructed system is transformed into a fuzzy supply chain network model with the uncertain customer demand and the lead times. In Section 3, we develop a stability theorem of the supply chain network. In Section 4, a simulation example is provided to show the effectiveness of the proposed fuzzy robust strategy for the supply chain network system. In Section 5, discussions are given. Finally, some conclusions are presented in Section 6.

2. Models of Supply Chain Network

2.1. Basic Model of Supply Chain Network. The basic notations in models of supply chain network are listed in Notations section.

We consider a type of dynamic supply chain network with a dual-echelon network including s manufacturers and t distributors, and the microstructure of the network in Figure 1 illustrates the structure characteristics of the supply chain network.

In Figure 1, $\mathbf{L} = (l_{ab})_{s\times t}$ $(0 \leq l_{ab} \leq 1)$ is the structure parameter matrix of supply and demand between manufacturers and distributors; if $0 < l_{ab} \leq 1$, there is a relationship of supply and demand between manufacturer a and distributor b; if $l_{ab} = 0$, there is not a relationship of supply and demand between manufacturer a and distributor b.

From Figure 1, a basic inventory model of the dynamic supply chain network is constructed as follows:

$$\begin{aligned} x_a(k+1) &= x_a(k) + u_a(k) - \sum_{b=1}^{t} l_{ab} u_{ab}(k), \\ y_b(k+1) &= y_b(k) + \sum_{a=1}^{s} l_{ab} u_{ab}(k) - w_b(k). \end{aligned} \tag{1}$$

In supply chain management, lead time is an important indicator to measure the rapid response ability of supply chain for the rapid changes in the market demand. In reality, the lead time is very common in each link of supply chain

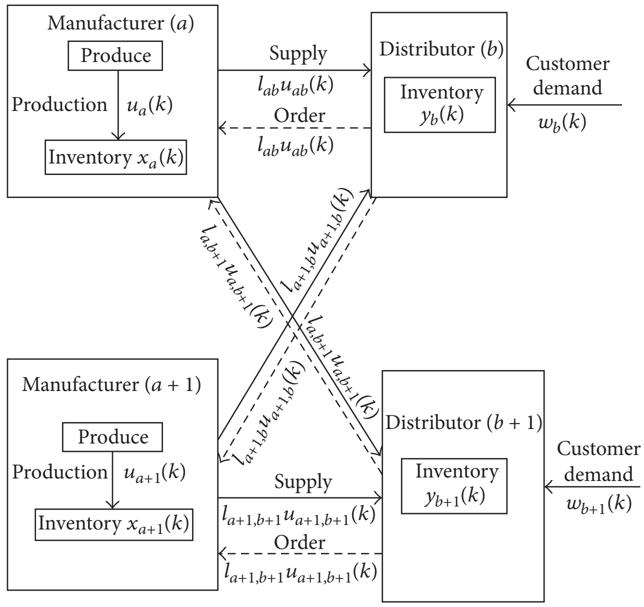

FIGURE 1: Microstructure of supply chain network.

operation, which is influenced by many kinds of economies and technologies. What is more, the lead time not only increases the management cost of firms, but also causes the inefficient operations of the supply chain. Based on (1), a basic model of the supply chain network with the production lead times and the ordering lead times can be described as follows:

$$\begin{aligned} x_a(k+1) &= x_a(k) + u_a(k) + u_a(k-\tau_a) \\ &\quad - \sum_{b=1}^{t} l_{ab}u_{ab}(k), \\ y_b(k+1) &= y_b(k) + \sum_{a=1}^{s} l_{ab}u_{ab}(k) + \sum_{a=1}^{s} l_{ab}u_{ab}(k-\tau_{ab}) \\ &\quad - w_b(k). \end{aligned} \tag{2}$$

2.2. T-S Fuzzy Model of Supply Chain Network with Uncertain Demand and Lead Times. For the supply chain network with the uncertain demand and the lead times, there are different basic dynamic inventory models at different periods. In order to reduce the cost of the supply chain network effectively, the switching action will often occur among the different basic models. The different switching rules will affect the performance of the supply chain network to different extent. Takagi-Sugeno (T-S) fuzzy systems, suggested by Takagi and Sugeno in 1985 [25], consist of fuzzy If...Then rules with linguistic terms in antecedents and analytic dynamical equations in the consequents, which can be viewed as the expansion of piecewise linear partition based on "fuzzy partition" of input space [26]. In order to realize the flexible switching among the different basic models and restrain large fluctuations of the system variables in the switching processes, by utilizing T-S fuzzy systems and increasing the cost output equation, under the uncertain customer demand, the discrete T-S fuzzy model of the dynamic supply chain network with the production lead times and the ordering lead times can be described as

R^i: if $x_1(k)$ is $M_1^i, \ldots, x_j(k)$ is $M_j^i, \ldots$, and $x_n(k)$ is M_n^i, then

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{A}_i\mathbf{x}(k) + \mathbf{B}_i\mathbf{u}(k) + \sum_{e=1}^{g}\mathbf{B}_{ie}\mathbf{u}(k-\tau_e) \\ &\quad + \mathbf{B}_{wi}\mathbf{w}(k), \\ z(k) &= \mathbf{C}_i\mathbf{x}(k) + \mathbf{D}_i\mathbf{u}(k) + \sum_{e=1}^{g}\mathbf{D}_{ie}\mathbf{u}(k-\tau_e), \\ \mathbf{x}(k) &= \boldsymbol{\varphi}(k), \quad k \in \{0, 1, \ldots, N\}, \end{aligned} \tag{3}$$

where $\boldsymbol{\varphi}(k)$ is the initial condition; $\mathbf{x}(k)$ is the inventory state vector at period k, $\mathbf{x}(k) = [x_1(k) \ \cdots \ x_a(k) \ \cdots \ x_s(k) \ y_1(k) \ \cdots \ y_b(k) \ \cdots \ y_t(k)]^T$; $\mathbf{u}(k)$ is the production and ordering control vector at period k; $\mathbf{u}(k-\tau_e)$ is the production and ordering control vector with lead times at period k; $e = 1, \ldots, a, \ldots, s, 11, \ldots, ab, \ldots st$; $g = s + st$; $\mathbf{w}(k)$ is the customer demand vector at period k, which is assumed to belong to $l_2[0,\infty)$. $\mathbf{A}_i = \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & \ddots & \\ & & & 1 \end{bmatrix}_{(s+t)\times(s+t)}$ is the inventory status coefficient matrix, which embodies the inventory level of the supply chain network; $\mathbf{B}_i = \begin{bmatrix} \mathbf{I}_s & -\mathbf{M}_1 \\ \mathbf{0} & \mathbf{M}_2 \end{bmatrix}_{(s+t)\times(s+st)}$ ($\mathbf{I}_s = \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & \ddots & \\ & & & 1 \end{bmatrix}_{s\times s}$, $\mathbf{M}_1 = \begin{bmatrix} \mathbf{L}_1 & & & & \\ & \ddots & & & \\ & & \mathbf{L}_a & & \\ & & & \ddots & \\ & & & & \mathbf{L}_s \end{bmatrix}_{s\times st}$, $\mathbf{L}_a = [l_{a1} \ \cdots \ l_{ab} \ \cdots \ l_{at}]_{1\times t}$, $\mathbf{M}_2 = [\mathbf{H}_1 \ \cdots \ \mathbf{H}_a \ \cdots \ \mathbf{H}_s]_{t\times ts}$, $\mathbf{H}_a = \begin{bmatrix} l_{a1} & & & & \\ & \ddots & & & \\ & & l_{ab} & & \\ & & & \ddots & \\ & & & & l_{at} \end{bmatrix}_{t\times t}$) is the production or ordering coefficient matrix, which embodies manufacturers' production capacity or distributors' ordering quantity; for the production delay coefficient matrix caused by lead time, $\mathbf{B}_{ie} = \left[\begin{smallmatrix} \mathbf{I}_s & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{smallmatrix}\right]_{(s+t)\times(s+st)}$; for the ordering delay coefficient matrix caused by lead time, $\mathbf{B}_{ie} = \left[\begin{smallmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_2 \end{smallmatrix}\right]_{(s+t)\times(s+st)}$; $\mathbf{B}_{wi} = \left[\begin{smallmatrix} \mathbf{0} \\ -\mathbf{I} \end{smallmatrix}\right]_{(s+t)\times(s+t)}$ is the customer demand coefficient matrix; $\mathbf{C}_i = [c_{h1} \ \cdots \ c_{ha} \ \cdots \ c_{hs} \ c_{r1} \ \cdots \ c_{rb} \ \cdots \ c_{rt}]_{1\times(s+t)}$ is the inventory cost coefficient matrix; $\mathbf{D}_i = [c_{m1} \ \cdots \ c_{ma} \ \cdots \ c_{ms} \ \mathbf{c}_{o1} \ \cdots \ \mathbf{c}_{oa} \ \cdots \ \mathbf{c}_{os}]_{1\times(s+st)}$ is the cost coefficient matrix of the production and ordering, where $\mathbf{c}_{oa}$ is distributors' unit ordering cost matrix from manufacturer a ($\mathbf{c}_{oa} = [l_{a1}c_{oa1} \ \cdots \ l_{ab}c_{oab} \ \cdots \ l_{at}c_{oat}]$); for the cost coefficient matrix of production with lead times, $\mathbf{D}_{ie} = [c_{m1} \ \cdots \ c_{ma} \ \cdots \ c_{ms} \ \mathbf{0}]_{1\times(s+st)}$; for the cost coefficient matrix of ordering with lead times, $\mathbf{D}_{ie} = [\mathbf{0} \ \mathbf{c}_{o1} \ \cdots \ \mathbf{c}_{oa} \ \cdots \ \mathbf{c}_{os}]_{1\times(s+st)}$.

In this article, the fuzzy supply chain network system (3) is described by deviation variables, which are the differences between the actual operation values and the nominal values.

By singleton fuzzifier, product inference, and centre-average defuzzifier, the fuzzy supply chain network system (3) is inferred as follows:

$$\begin{aligned} \mathbf{x}(k+1) &= \sum_{i=1}^{r} h_i(\mathbf{x}(k)) \\ &\cdot \left[\mathbf{A}_i\mathbf{x}(k) + \mathbf{B}_i\mathbf{u}(k) + \sum_{e=1}^{g}\mathbf{B}_{ie}\mathbf{u}(k-\tau_e) + \mathbf{B}_{wi}\mathbf{w}(k)\right], \\ z(k) &= \sum_{i=1}^{r} h_i(\mathbf{x}(k)) \\ &\cdot \left[\mathbf{C}_i\mathbf{x}(k) + \mathbf{D}_i\mathbf{u}(k) + \sum_{e=1}^{g}\mathbf{D}_{ie}\mathbf{u}(k-\tau_e)\right], \end{aligned} \tag{4}$$

where $h_i(\mathbf{x}(k)) = \mu_i(\mathbf{x}(k))/\sum_{i=1}^{r}\mu_i(\mathbf{x}(k))$, $\mu_i(\mathbf{x}(k)) = \prod_{j=1}^{n} M_j^i(x_j(k))$, $M_j^i(x_j(k))$ is the grade of membership of $x_j(k)$ in the fuzzy set M_j^i, $\mu_i(\mathbf{x}(k))$ is the membership degree of the ith rule. For simplicity, we omit $\mathbf{x}(k)$ in $h_i(\mathbf{x}(k))$.

3. Fuzzy Robust Strategy of Dynamic Supply Chain Network

3.1. Inhibition Rate of Fuzzy Robust Controller. Fuzzy robust control can effectively help firms to cope with the operational lead times and the uncertain customer demand and guarantee the asymptotic stability of the supply chain network. We use the parameter γ as the inhibition rate of the fuzzy robust controller; namely,

$$\frac{\left\|\sum_{i=1}^{r}\sum_{j=1}^{r} h_i h_j \left[\left(\mathbf{C}_i - \mathbf{D}_i\mathbf{K}_j\right)\mathbf{x}(k) - \sum_{e=1}^{g}\mathbf{D}_{ie}\mathbf{K}_{je}\mathbf{x}(k-\tau_e)\right]\right\|_2}{\|\mathbf{w}(k)\|_2} \le \gamma, \tag{5}$$

where $\|\cdot\|_2$ is $l_2 \in [0,\infty)$ norm. Inequality (5) describes the system gain characteristic from the uncertain customer demand variable $\mathbf{w}(k)$ to the total cost $z(k)$ of the supply chain network; namely, the smaller the parameter γ is, the better the performance of the supply chain network system will be, and the fuzzy robust strategy can make inequality (5) achieve the ideal value.

3.2. Fuzzy Control Strategy for Discrete Switched Supply Chain Network. Based on the principle of the parallel distributed compensation, the design of a fuzzy controller is to synthesize a local feedback controller for each subsystem. Then the local state feedback controller is formulated as follows:

controller rule K^i: if $x_1(k)$ is $M_1^i, \ldots, x_j(k)$ is $M_j^i, \ldots$, and $x_n(k)$ is M_n^i, then

$$\begin{aligned} \mathbf{u}(k) &= -\mathbf{K}_i\mathbf{x}(k), \\ \mathbf{u}(k-\tau_e) &= -\mathbf{K}_{ie}\mathbf{x}(k-\tau_e), \end{aligned} \tag{6}$$

where $\mathbf{K}_i$ and $\mathbf{K}_{ie}$ are the state feedback gain matrix and the state feedback gain matrix with the lead times, respectively.

The state feedback controller of the global supply chain network can be expressed as

$$\begin{aligned} \mathbf{u}(k) &= -\sum_{i=1}^{r} h_i\mathbf{K}_i\mathbf{x}(k), \\ \mathbf{u}(k-\tau_e) &= -\sum_{i=1}^{r} h_i\mathbf{K}_{ie}\mathbf{x}(k-\tau_e). \end{aligned} \tag{7}$$

Then the fuzzy control system of the supply chain network can be written as

$$\begin{aligned} \mathbf{x}(k+1) &= \sum_{i=1}^{r}\sum_{j=1}^{r} h_i h_j \cdot \left[\left(\mathbf{A}_i - \mathbf{B}_i\mathbf{K}_j\right)\mathbf{x}(k) \right. \\ &\left. - \sum_{e=1}^{g}\mathbf{B}_{ie}\mathbf{K}_{je}\mathbf{x}(k-\tau_e) + \mathbf{B}_{wi}\mathbf{w}(k)\right], \\ z(k) &= \sum_{i=1}^{r}\sum_{j=1}^{r} h_i h_j \cdot \left[\left(\mathbf{C}_i - \mathbf{D}_i\mathbf{K}_j\right)\mathbf{x}(k) \right. \\ &\left. - \sum_{e=1}^{g}\mathbf{D}_{ie}\mathbf{K}_{je}\mathbf{x}(k-\tau_e)\right]. \end{aligned} \tag{8}$$

Before further analysis, we introduce the following definitions as the preparation for Theorem 3.

Definition 1 (see [27]). A cluster of fuzzy sets $\{F_j^u, u = 1, 2, \ldots, q_j\}$ are said to be a standard fuzzy partition (SFP) in the universe X if each F_j^u is a normal fuzzy set and F_j^u ($u = 1, 2, \ldots, q_j$) are full-overlapped in the universe X. q_j is said to be the number of fuzzy partitions of the jth input variable on X.

Definition 2 (see [27]). For a given fuzzy system, an overlapped-rules group with the largest amount of rules is said to be a maximal overlapped-rules group (MORG).

The stability theorem of the supply chain network will be given in the form of Theorem 3.

Theorem 3. *For the fuzzy supply chain network system (8) with lead times and SFP inputs, if there exist a given scalar $\gamma > 0$, local common positive definite matrices $\mathbf{P}_c$ and $\mathbf{Q}_{ec}$, and matrices $\mathbf{K}_{ic}$, $\mathbf{K}_{jc}$, $\mathbf{K}_{iec}$, $\mathbf{K}_{jec}$ in $\mathbf{G}_c$ satisfying*

$$\begin{bmatrix} -\mathbf{P}_c + \sum_{e=1}^{g} \mathbf{Q}_{ec} & * & * & * & * \\ \mathbf{0} & -\widehat{\mathbf{Q}} & * & * & * \\ \mathbf{0} & \mathbf{0} & -\gamma^2 \mathbf{I} & * & * \\ \mathbf{A}_i - \mathbf{B}_i \mathbf{K}_{ic} & -\mathbf{\Pi}_1 & \mathbf{B}_{wi} & -\mathbf{P}_c & * \\ \mathbf{C}_i - \mathbf{D}_i \mathbf{K}_{ic} & -\mathbf{\Pi}_2 & \mathbf{0} & \mathbf{0} & -\mathbf{I} \end{bmatrix} < \mathbf{0}, \quad i \in I_{\mathbf{c}},$$

$$\begin{bmatrix} -4\mathbf{P}_c + 4\sum_{e=1}^{g} \mathbf{Q}_{ec} & * & * & * & * \\ \mathbf{0} & -4\widehat{\mathbf{Q}} & * & * & * \\ \mathbf{0} & \mathbf{0} & -4\gamma^2 \mathbf{I} & * & * \\ \mathbf{A}_i - \mathbf{B}_i \mathbf{K}_{jc} + \mathbf{A}_j - \mathbf{B}_j \mathbf{K}_{ic} & -\mathbf{\Phi}_1 & \mathbf{B}_{wi} + \mathbf{B}_{wj} & -\mathbf{P}_c & * \\ \mathbf{C}_i - \mathbf{D}_i \mathbf{K}_{jc} + \mathbf{C}_j - \mathbf{D}_j \mathbf{K}_{ic} & -\mathbf{\Phi}_2 & \mathbf{0} & \mathbf{0} & -\mathbf{I} \end{bmatrix}$$
$$< \mathbf{0}, \quad i < j, \ i, j \in I_c, \tag{9}$$

then the fuzzy supply chain network system (8) is robustly asymptotically stable under the performance γ, where I_c is the set of the rule numbers included in $\mathbf{G}_c$, $\mathbf{G}_c$ denotes the cth MORG, $c = 1, 2, \ldots, \prod_{j=1}^{n}(m_j - 1)$, m_j is the number of the fuzzy partitions of the jth input variable, $\widehat{\mathbf{Q}} = \operatorname{diag}\{\mathbf{Q}_{1c} \ \cdots \ \mathbf{Q}_{ec} \ \cdots \ \mathbf{Q}_{gc}\}$,

$$\begin{aligned} \mathbf{\Pi}_1 &= [\mathbf{B}_{i1}\mathbf{K}_{i1c} \ \cdots \ \mathbf{B}_{ie}\mathbf{K}_{iec} \ \cdots \ \mathbf{B}_{ig}\mathbf{K}_{igc}], \\ \mathbf{\Pi}_2 &= [\mathbf{D}_{i1}\mathbf{K}_{i1c} \ \cdots \ \mathbf{D}_{ie}\mathbf{K}_{iec} \ \cdots \ \mathbf{D}_{ig}\mathbf{K}_{igc}], \\ \mathbf{\Phi}_1 &= [\mathbf{B}_{i1}\mathbf{K}_{j1c} + \mathbf{B}_{j1}\mathbf{K}_{i1c} \ \cdots \ \mathbf{B}_{ie}\mathbf{K}_{jec} + \mathbf{B}_{je}\mathbf{K}_{iec} \ \cdots \ \mathbf{B}_{ig}\mathbf{K}_{jgc} + \mathbf{B}_{jg}\mathbf{K}_{igc}], \\ \mathbf{\Phi}_2 &= [\mathbf{D}_{i1}\mathbf{K}_{j1c} + \mathbf{D}_{j1}\mathbf{K}_{i1c} \ \cdots \ \mathbf{D}_{ie}\mathbf{K}_{jec} + \mathbf{D}_{je}\mathbf{K}_{iec} \ \cdots \ \mathbf{D}_{ig}\mathbf{K}_{jgc} + \mathbf{D}_{jg}\mathbf{K}_{igc}]. \end{aligned} \tag{10}$$

Proof. The proof processes of Theorem 3 in this paper are similar to those of Theorems 1 and 2 in [28], which are omitted for the sake of brevity. □

For the supply chain network with the uncertain customer demand and the lead times, we propose the following fuzzy robust strategy, which consists of the fuzzy switched strategy and the fuzzy control strategy.

(1) Fuzzy switched strategy

① When a manufacturer's inventory is less than the safety inventory, the manufacturer will urgently produce the goods; If a manufacturer's inventory is more than the safety inventory and less than the expected inventory, the manufacture will normally produce the goods; If a manufacturer's inventory is more than the expected inventory, the manufacture will stop producing.

② When a distributor's inventory is less than the safety inventory, the distributor will urgently order the goods; If a distributor's inventory is more than the safety inventory and less than the expected inventory, the distributor will normally order the goods; If a distributor's inventory is more than the expected inventory, the distributor will stop ordering.

③ According to (4), when the manufacturers and the distributors lie in different inventories, there are the different fuzzy control rules. When manufactures' inventories and distributors' inventories change, the switching actions will occur among fuzzy control rules. Due to the fuzzy membership function, the switching actions can be seen as a flexible switching, which is also called a robust switching.

(2) Fuzzy control strategy

① If a proper inhibition rate γ is given, by solving (9), we can obtain the state feedback gain matrices. The closed-loop negative feedback control can be realized by using state feedback controller (7). Then all variables in the fuzzy supply chain network (8) can realize robust stabilization under the uncertain demand and the lead times.

② The optimal inhibition rate γ can be obtained according to Figure 2.

4. Simulation Research

4.1. Modeling Supply Chain Network with 2 Manufacturers and 2 Distributors. In practice, material processing and material acquisition of steel industry are very complicated processes because there are so many upstream and downstream members, materials, and semifinished products. To assess the performance of the designed fuzzy robust strategy and to gain further insights into the dynamical characteristics of the supply chain network with the lead times under the uncertain customer demand, we choose an H-beam supply chain network of North Tai Steel Group in China as a simulation object. And this supply chain network consists of 2 manufacturers and 2 distributors.

In this section, according to the inventory levels, manufacturers will develop the production strategy to avoid the inventory backlog or increase opportunity cost; at the same time, according to manufacturers' inventory levels, distributors will formulate the ordering strategy. Thus, the

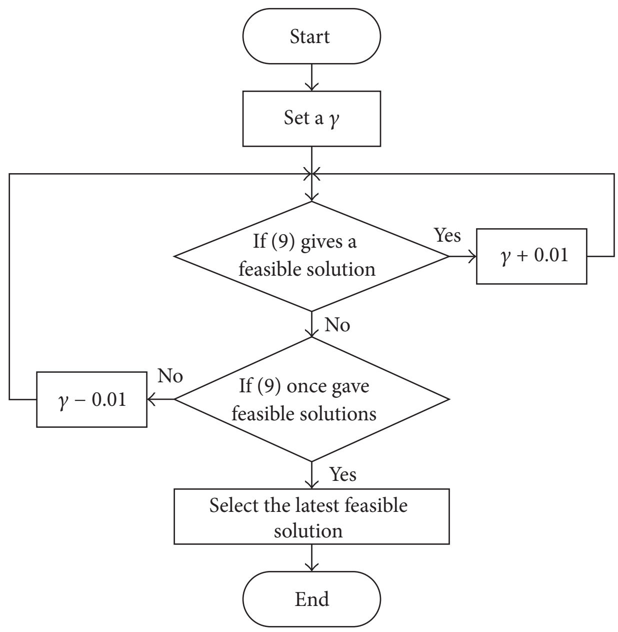

FIGURE 2: Flow chart of selecting the optimal inhibition rate.

dynamic model of the supply chain network with the lead times is established at period k as follows:

$$\begin{aligned} x_1(k+1) &= x_1(k) + u_1(k) + u_1(k-\tau_1) - l_{11}u_{11}(k) \\ &\quad - l_{12}u_{12}(k), \\ x_2(k+1) &= x_2(k) + u_2(k) + u_2(k-\tau_2) - l_{21}u_{21}(k) \\ &\quad - l_{22}u_{22}(k), \\ y_1(k+1) &= y_1(k) + l_{11}u_{11}(k) + l_{11}u_{11}(k-\tau_{11}) \\ &\quad + l_{21}u_{21}(k) + l_{21}u_{21}(k-\tau_{21}) \\ &\quad - w_1(k), \\ y_2(k+1) &= y_2(k) + l_{12}u_{12}(k) + l_{12}u_{12}(k-\tau_{12}) \\ &\quad + l_{22}u_{22}(k) + l_{22}u_{22}(k-\tau_{22}) \\ &\quad - w_2(k), \end{aligned} \tag{11}$$

where $x_1(k)$, $x_2(k)$, $y_1(k)$, and $y_2(k)$ are manufacturer 1's inventory, manufacturer 2's inventory, distributor 1's inventory, and distributor 2's inventory of the supply chain network at period k, respectively, which are state variables. $u_1(k)$, $u_2(k)$, $u_{11}(k)$, $u_{12}(k)$, $u_{21}(k)$, and $u_{22}(k)$ are manufacturer 1's production, manufacturer 2's production, distributer 1's ordering quantity from manufacturer 1, distributor 2's ordering quantity from manufacturer 1, distributor 1's ordering quantity from manufacturer 2, and distributor 2's ordering quantity from manufacturer 2, respectively, which are the control variables. $u_1(k-\tau_1)$ and $u_2(k-\tau_2)$ are the productions with lead times τ_1 and τ_2; $u_{11}(k-\tau_{11})$, $u_{12}(k-\tau_{12})$, $u_{21}(k-\tau_{21})$, and $u_{22}(k-\tau_{22})$ are the ordering quantities with lead times τ_{11}, τ_{12}, τ_{21}, and τ_{22}, in which τ_e $(e = 1, 2, 11, 12, 21, 22)$ is independent lead time parameter. Let $\tau' = \tau_1 = \tau_2$ and $\tau'' = \tau_{11} = \tau_{12} = \tau_{21} = \tau_{22}$. $w_1(k)$ and $w_2(k)$ are the customer demand at period k, which are uncertain variables. l_{11}, l_{12}, l_{21}, and l_{22} are the ordering rates.

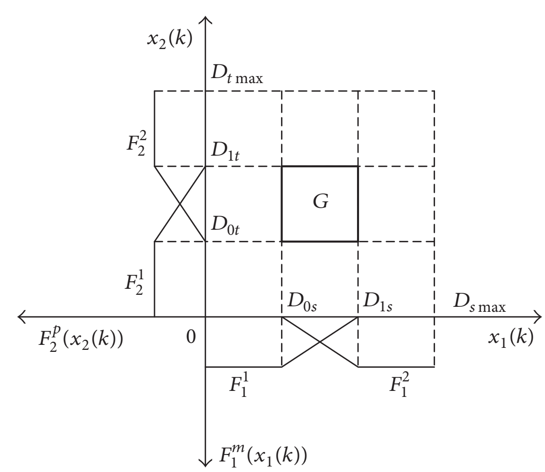

FIGURE 3: Fuzzy membership functions.

Suppose $x_1(k)$ and $x_2(k)$ can be measured, the fuzzy partitions of $x_1(k)$ and $x_2(k)$ are $F_1^m(x_1(k))$ $(m = 1, 2)$ and $F_2^p(x_2(k))$ $(p = 1, 2)$, respectively, and conform to the conditions of SFP. Let $M_1^1 = M_1^2 = F_1^1$, $M_1^3 = M_1^4 = F_1^2$, $M_2^1 = M_2^3 = F_2^1$, $M_2^2 = M_2^4 = F_2^2$. The fuzzy sets of $x_1(k)$ and $x_2(k)$ represented by the membership functions are shown in Figure 3 (D_{0s}, D_{1s}, and $D_{s\max}$ are manufacturer 1's safety inventory, expected inventory, and maximum inventory, respectively; D_{0t}, D_{1t}, and $D_{t\max}$ are manufacturer 2's safety inventory, expected inventory, and maximum inventory, respectively).

In Figure 3, we can see that there exists a MORG containing 4 fuzzy rules. According to Theorem 3, by considering the lead times, the production capacity, the supply chain structure, and the uncertain customer demand, the two-echelon supply chain network model can be transformed into the following fuzzy model:

R^i: if $x_1(k)$ is M_1^i and $x_2(k)$ is M_2^i, then

$$\begin{aligned}\mathbf{x}(k+1) &= \sum_{i=1}^{r} h_i \left[\mathbf{A}_i\mathbf{x}(k) + \mathbf{B}_i\mathbf{u}(k) + \mathbf{B}_{i1}\mathbf{u}\left(k-\tau'\right)\right.\\ &\quad \left. + \mathbf{B}_{i2}\mathbf{u}\left(k-\tau''\right) + \mathbf{B}_{wi}\mathbf{w}(k)\right],\\ z(k) &= \sum_{i=1}^{r} h_i \left[\mathbf{C}_i\mathbf{x}(k) + \mathbf{D}_i\mathbf{u}(k) + \mathbf{D}_{i1}\mathbf{u}\left(k-\tau'\right)\right.\\ &\quad \left. + \mathbf{D}_{i2}\mathbf{u}\left(k-\tau''\right)\right],\end{aligned} \tag{12}$$

where $r = 4$, $\mathbf{x}^T(k) = [x_1(k)\ \ x_2(k)\ \ y_1(k)\ \ y_2(k)]$, $\mathbf{u}^T(k) = [u_1(k)\ \ u_2(k)\ \ u_{11}(k)\ \ u_{12}(k)\ \ u_{21}(k)\ \ u_{22}(k)]$.

Based on historical data, l_{ab} will be assigned different values for different fuzzy rules: when $i = 1$, $l_{11} = l_{12} = l_{21} = l_{22} = 0.5$; when $i = 2$, $l_{11} = 0.35$, $l_{12} = 0.43$, $l_{21} = 0.65$, and $l_{22} = 0.57$; when $i = 3$, $l_{11} = 0.65$, $l_{12} = 0.57$, $l_{21} = 0.35$, and $l_{22} = 0.43$; when $i = 4$, $l_{11} = l_{12} = l_{21} = l_{22} = 0.5$. Therefore, we have

$$\mathbf{A}_1 = \mathbf{A}_2 = \mathbf{A}_3 = \mathbf{A}_4 = \begin{bmatrix} 1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix},$$

$$\mathbf{B}_1 = \begin{bmatrix} 1 & 0 & -0.5 & -0.5 & 0 & 0\\ 0 & 1 & 0 & 0 & -0.5 & -0.5\\ 0 & 0 & 0.5 & 0 & 0.5 & 0\\ 0 & 0 & 0 & 0.5 & 0 & 0.5\end{bmatrix},$$

$$\mathbf{B}_2 = \begin{bmatrix} 1 & 0 & -0.35 & -0.43 & 0 & 0\\ 0 & 1 & 0 & 0 & -0.65 & -0.57\\ 0 & 0 & 0.35 & 0 & 0.65 & 0\\ 0 & 0 & 0 & 0.43 & 0 & 0.57\end{bmatrix},$$

$$\mathbf{B}_3 = \begin{bmatrix} 1 & 0 & -0.65 & -0.57 & 0 & 0\\ 0 & 1 & 0 & 0 & -0.35 & -0.43\\ 0 & 0 & 0.65 & 0 & 0.35 & 0\\ 0 & 0 & 0 & 0.57 & 0 & 0.43\end{bmatrix},$$

$$\mathbf{B}_4 = \begin{bmatrix} 1 & 0 & -0.5 & -0.5 & 0 & 0\\ 0 & 1 & 0 & 0 & -0.5 & -0.5\\ 0 & 0 & 0.5 & 0 & 0.5 & 0\\ 0 & 0 & 0 & 0.5 & 0 & 0.5\end{bmatrix},$$

$$\mathbf{B}_{11} = \mathbf{B}_{21} = \mathbf{B}_{31} = \mathbf{B}_{41} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix},$$

$$\mathbf{B}_{12} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0.5 & 0 & 0.5 & 0\\ 0 & 0 & 0 & 0.5 & 0 & 0.5\end{bmatrix},$$

$$\mathbf{B}_{22} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0.35 & 0 & 0.65 & 0\\ 0 & 0 & 0 & 0.43 & 0 & 0.57\end{bmatrix},$$

$$\mathbf{B}_{32} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0.65 & 0 & 0.35 & 0\\ 0 & 0 & 0 & 0.57 & 0 & 0.43\end{bmatrix},$$

$$\mathbf{B}_{42} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0.5 & 0 & 0.5 & 0\\ 0 & 0 & 0 & 0.5 & 0 & 0.5\end{bmatrix},$$

$$\mathbf{B}_{w1} = \mathbf{B}_{w2} = \mathbf{B}_{w3} = \mathbf{B}_{w4} = \begin{bmatrix} 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & -1 & 0\\ 0 & 0 & 0 & -1\end{bmatrix},$$

$$\mathbf{C}_1 = \mathbf{C}_2 = \mathbf{C}_3 = \mathbf{C}_4 = \left[c_{h1}\ \ c_{h2}\ \ c_{r1}\ \ c_{r2}\right],$$

$$\mathbf{D}_1 = \left[c_{mJ1}\ \ c_{mJ2}\ \ 0.5c_{o11}\ \ 0.5c_{o12}\ \ 0.5c_{o21}\ \ 0.5c_{o22}\right],$$

$$\mathbf{D}_2 = \left[c_{mJ1}\ \ c_{mN2}\ \ 0.35c_{o11}\ \ 0.43c_{o12}\ \ 0.65c_{o21}\ \ 0.57c_{o22}\right],$$

$$\mathbf{D}_3 = \left[c_{mN1}\ \ c_{mJ2}\ \ 0.65c_{o11}\ \ 0.57c_{o12}\ \ 0.35c_{o21}\ \ 0.43c_{o22}\right],$$

$$\mathbf{D}_4 = \left[c_{mN1}\ \ c_{mN2}\ \ 0.5c_{o11}\ \ 0.5c_{o12}\ \ 0.5c_{o21}\ \ 0.5c_{o22}\right],$$

$$\mathbf{D}_{11} = \left[c_{mJ1}\ \ c_{mJ2}\ \ 0\ \ 0\ \ 0\ \ 0\right],$$

$$\mathbf{D}_{21} = \left[c_{mJ1}\ \ c_{mN2}\ \ 0\ \ 0\ \ 0\ \ 0\right],$$

$$\mathbf{D}_{31} = \left[c_{mN1}\ \ c_{mJ2}\ \ 0\ \ 0\ \ 0\ \ 0\right],$$

$$\mathbf{D}_{41} = \left[c_{mN1}\ \ c_{mN2}\ \ 0\ \ 0\ \ 0\ \ 0\right],$$

$$\mathbf{D}_{12} = \left[0\ \ 0\ \ 0.5c_{o11}\ \ 0.5c_{o12}\ \ 0.5c_{o21}\ \ 0.5c_{o22}\right],$$

$$\mathbf{D}_{22} = \left[0\ \ 0\ \ 0.35c_{o11}\ \ 0.43c_{o12}\ \ 0.65c_{o21}\ \ 0.57c_{o22}\right],$$

$$\mathbf{D}_{32} = \begin{bmatrix} 0 & 0 & 0.65c_{o11} & 0.57c_{o12} & 0.35c_{o21} & 0.43c_{o22} \end{bmatrix},$$
$$\mathbf{D}_{42} = \begin{bmatrix} 0 & 0 & 0.5c_{o11} & 0.5c_{o12} & 0.5c_{o21} & 0.5c_{o22} \end{bmatrix}. \tag{13}$$

We define that c_{h1}, c_{h2}, c_{r1}, and c_{r2} are manufacturer 1's unit inventory cost, manufacturer 2's unit inventory cost, distributor 1's unit inventory cost, and distributor 2's unit inventory cost, respectively; $c_{m1} = c_{mN1}$ and $c_{m2} = c_{mN2}$ are the manufacturer 1's unit manufacturing costs and the manufacturer 2's unit manufacturing costs under the normal production condition, respectively; $c_{m1} = c_{mJ1}$ and $c_{m2} = c_{mJ2}$ are manufacturer 1's unit inventory costs and manufacturer 2's unit inventory costs under the JIT condition, respectively; c_{o11}, c_{o12}, c_{o21}, and c_{o22} are distributor 1's unit ordering cost from manufacturer 1, distributor 2's unit ordering cost from manufacturer 1, distributor 1's unit ordering cost from manufacturer 2, and distributor 2's unit ordering cost from manufacturer 2, respectively.

Then, according to the established T-S fuzzy model, the relative fuzzy state feedback controller of the supply chain network is designed as follows:

K^i: if $x_1(k)$ is M_1^i and $x_2(k)$ is M_2^i, then

$$\mathbf{u}(k) = -\sum_{i=1}^{r} h_i \mathbf{K}_{i1} \mathbf{x}(k),$$
$$\mathbf{u}\left(k-\tau'\right) = -\sum_{i=1}^{r} h_i \mathbf{K}_{i11} \mathbf{x}\left(k-\tau'\right), \tag{14}$$
$$\mathbf{u}\left(k-\tau''\right) = -\sum_{i=1}^{r} h_i \mathbf{K}_{i21} \mathbf{x}\left(k-\tau''\right).$$

Base on the practices, all parameters of the model are set as $c_{h1} = 1.3$, $c_{h2} = 1.45$, $c_{r1} = 0.95$, $c_{r2} = 1$, $c_{mN1} = 2.3$, $c_{mJ1} = 3$, $c_{mN2} = 2.1$, $c_{mJ2} = 2.63$, $c_{o11} = 3.6$, $c_{o12} = 4.2$, $c_{o21} = 3.95$, $c_{o22} = 3.81$ (10^4 RMB/ton), $D_{0s} = 10$, $D_{1s} = 30$, $D_{0t} = 8$, $D_{1t} = 33$ (10^5 ton).

4.2. Simulation Analysis. Let the uncertain inhibition parameter $\gamma = 1.02$, and the fuzzy supply chain network system (12) is robustly stable because the corresponding results that meet Theorem 3 can be obtained by using the feasp solver in LMI Toolbox of Matlab as follows:

$$\mathbf{P}_1 = \begin{bmatrix} 31.5151 & 0.0051 & 0.0158 & 0.0169 \\ 0.0051 & 31.5180 & 0.0234 & 0.0248 \\ 0.0158 & 0.0234 & 31.6033 & 0.0978 \\ 0.0169 & 0.0248 & 0.0978 & 31.6153 \end{bmatrix},$$
$$\mathbf{Q}_{11} = \mathbf{Q}_{21} \tag{15}$$
$$= \begin{bmatrix} 10.5037 & 0 & 0 & 0 \\ 0 & 10.5037 & 0 & 0 \\ 0 & 0 & 10.5037 & 0 \\ 0 & 0 & 0 & 10.5037 \end{bmatrix}.$$

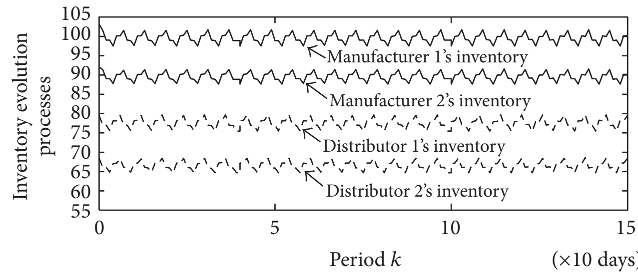

FIGURE 4: Inventory evolution processes under the common robust strategy ($\times 10^4$ ton).

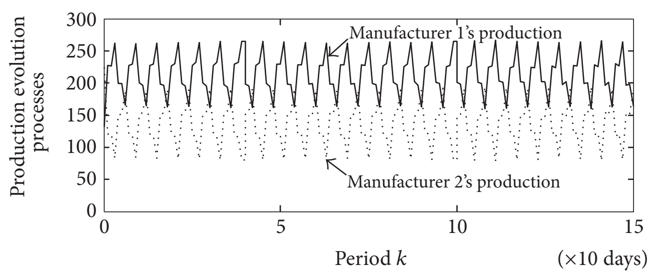

FIGURE 5: Production evolution processes under the common robust strategy ($\times 10^4$ ton).

Then, simulation experiments will be executed to compare the proposed fuzzy robust strategy with the common robust strategy for the inhibition effect on the lead times, the uncertain customer demand, and the fluctuation of the switching processes among subsystems of the supply chain network. Based on historical data, the initial values are set as $x_1(0) = 2$, $x_2(0) = 1.8$, $y_1(0) = 1.5$, $y_2(0) = 1.3$ (10^5 ton), and the normal values are set as $\overrightarrow{x}_1(k) = 10.2$, $\overrightarrow{x}_2(k) = 10$, $\overrightarrow{y}_1(k) = 9.8$, $\overrightarrow{y}_2(k) = 9.5$ (10^5 ton). Furthermore, the production lead times and the ordering lead times are both $\tau' = \tau'' = 2$ (×10 days).

Suppose the customer demand follows the normal distribution disturbance; that is, $w_1(k) = w_2(k) = N(3, 0.1^2)$. Figures 4–8 show the simulation results under the common robust strategy.

It can be seen from Figures 4–8 that the inventory levels, the productions, the ordering quantities, and the total cost of the supply chain network all fluctuate drastically under the common robust strategy.

In the same simulation environment, the simulation experiments are executed under the fuzzy robust strategy proposed in this article, and the simulation results can be seen in Figures 9–12.

By using the fuzzy robust strategy proposed in Section 3.2, manufacturers and distributors can adjust their production and ordering according to the inventory levels by the flexible switching actions among subsystems. Compared with the common robust strategy, the disturbances caused by the switching actions among subsystems, the lead times, and the uncertain customer demand can be restrained effectively under the fuzzy robust strategy. Therefore, the total cost of the supply chain network can be maintained in the ideal level. It

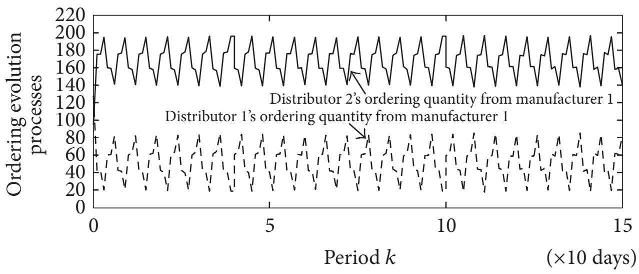

FIGURE 6: Ordering evolution processes from manufacturer 1 under the common robust strategy ($\times 10^4$ ton).

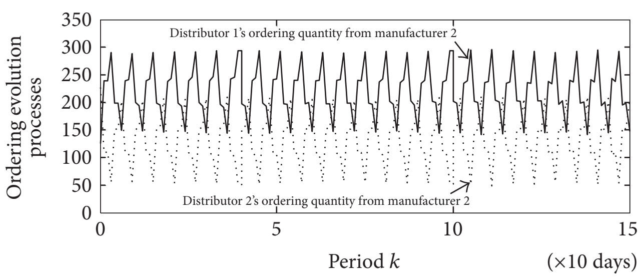

FIGURE 7: Ordering evolution processes from manufacturer 2 under the common robust strategy ($\times 10^4$ ton).

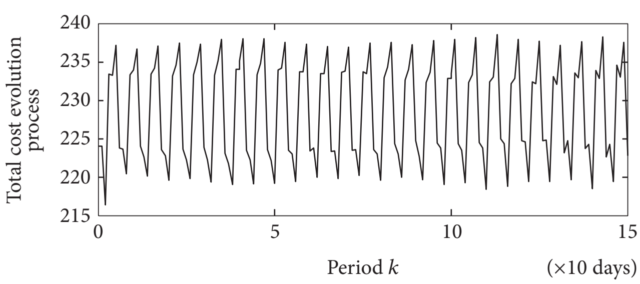

FIGURE 8: Total cost evolution process under the common robust strategy ($\times 10^8$ RMB).

is clear that the fuzzy robust strategy proposed in this article can ensure that the supply chain network is robustly stable.

5. Discussion

(1) In Theorem 3, the robustly asymptotically stable supply chain network system (8) is derived from the following definition.

Definition 4 (see [29]). Given a scalar $\gamma > 0$, the supply chain network system (8) is said to be robustly stable with the disturbance attenuation γ if two conditions as below are satisfied: (1) The closed-loop system (8) is robustly asymptotically stable when $\mathbf{w}(k) \equiv 0$. (2) Under zero-initial condition, the controlled output $\mathbf{z}(k)$ satisfies $\|\mathbf{z}(k)\|_2^2 < \gamma\|\mathbf{w}(k)\|_2^2$ for any nonzero $\mathbf{w}(k) \in \ell_2[0,\infty)$ and all admissible uncertainties.

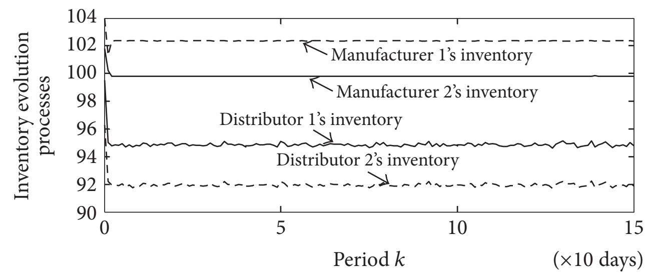

FIGURE 9: Inventory evolution processes under the fuzzy robust strategy ($\times 10^4$ ton).

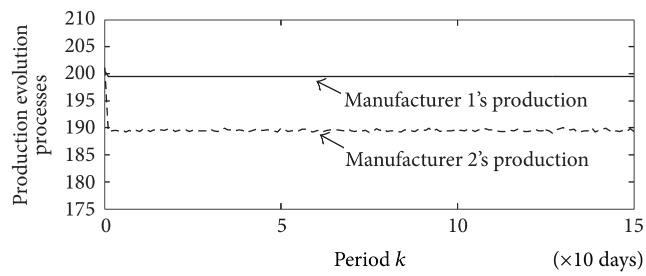

FIGURE 10: Production evolution processes under the fuzzy robust strategy ($\times 10^4$ ton).

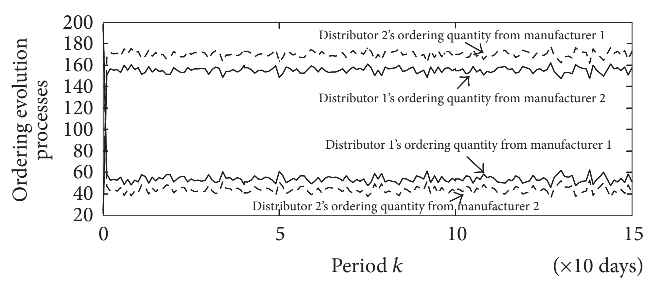

FIGURE 11: Ordering evolution processes under the fuzzy robust strategy ($\times 10^4$ ton).

The proof of Theorem 3 must satisfy the two conditions of Definition 4, and the similar detailed proof process can be seen in [28].

(2) Compared with the common robust strategy, the proposed fuzzy robust strategy can realize the flexible switching among subsystems of the supply chain network and effectively restrain the bullwhip effect. The bullwhip effect refers to the phenomenon of the amplification of demand variability from a downstream site to an upstream site in the supply chain [30]. The concept of bullwhip effect can describe the dynamic performance of our fuzzy robust controller.

6. Conclusions

In this article, we have studied the fuzzy robust control problem of dynamic supply chain network with the lead times and the uncertain demand. Taking into consideration the multiple sources of lead times in supply chain network, we focused on the production lead times and the ordering

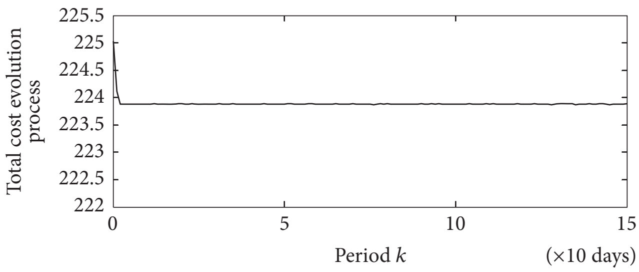

Figure 12: Total cost evolution process under the fuzzy robust strategy ($\times 10^8$ RMB).

lead times. We first built a basic model for the discrete dynamic supply chain network with the lead times and the uncertain demand. By considering the safety inventory and the expected inventory, the constructed basic model is transformed into a fuzzy switched supply chain network model, and then we developed the fuzzy switched strategy composed of the manufacturers' production strategy and the distributors' ordering strategy to keep the ideal total operation cost of the supply chain network. From the perspective of control system, we explored a fuzzy control strategy to realize the robust stability of the discrete switched supply chain network with the uncertain customer demand and the lead times. Simulation study indicates the fuzzy membership function does play an important role in reducing the fluctuation of system variables. Simulation results also verify the effectiveness and applicability of the proposed fuzzy robust strategy composed of the fuzzy switched strategy and the fuzzy control strategy in improving the robustness of the supply chain network with respect to the uncertain demand and the lead times. In practice, our work provides a new approach for supply chain managers to design better robust control strategy and improve supply chain performance. In the future researches, the structured model can be extended to the new supply chain model with supply and demand not only among manufacturers but also among distributors. And another new strategy will be developed for the supply chain network with the uncertain system parameters and the time-varying lead times.

Notations

$x_a(k)$: Manufacturer a's inventory at period k, $a = 1, 2, \ldots, s$
$y_b(k)$: Distributor b's inventory at period k, $b = 1, 2, \ldots, t$
$u_a(k)$: Manufacturer a's production at period k
$u_{ab}(k)$: The ordering from distributor b to manufacturer a at period k
$w_b(k)$: Distributor b's customer demand at period k
τ_a: Lead time during the production
τ_{ab}: Lead time during the ordering process
R^i: The ith fuzzy rule, $i = 1, 2, \ldots, r$
r: The number of IF-THEN rules
M_j^i: The fuzzy set, $j = 1, 2, \ldots, n$
$z(k)$: The total cost of the supply chain network at period k
l_{ab}: The coefficient of supply and demand between manufacturer a and distributor b
c_{ha}: Manufacturer a's unit inventory cost
c_{rb}: Distributor b's unit inventory cost
c_{ma}: Manufacturer a's unit producing cost
c_{oab}: Distributor b's unit ordering cost from manufacturer a.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Research Article

Optimal Retail Price Model for Partial Consignment to Multiple Retailers

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This paper investigates the product pricing decision-making problem under a consignment stock policy in a two-level supply chain composed of one supplier and multiple retailers. The effects of the supplier's wholesale prices and its partial inventory cost absorption of the retail prices of retailers with different market shares are investigated. In the partial product consignment model this paper proposes, the seller and the retailers each absorb part of the inventory costs. This model also provides general solutions for the complete product consignment and the traditional policy that adopts no product consignment. In other words, both the complete consignment and nonconsignment models are extensions of the proposed model (i.e., special cases). Research results indicated that the optimal retail price must be between 1/2 (50%) and 2/3 (66.67%) times the upper limit of the gross profit. This study also explored the results and influence of parameter variations on optimal retail price in the model.

1. Introduction

Advancements in information technology have changed product transaction process. The transaction process from sellers (upstream suppliers; suppliers) toward buyers (downstream vendors; retailers) has been partially replaced by e-commerce tools and logistics services. In the transaction process, most transaction costs are related to providing product information and convenient product access to the consumer. The use of e-commerce tools can reduce negotiation, ordering, and payment costs during the transaction process. The convenience of logistics services can reduce transaction costs. Although e-commerce improves transaction efficiency, not all goods are suitable for online transactions, particularly those that consumers must touch, observe, and "try out" in order to confirm the function or quality of the product before a purchase can be made at ease. In such transactions, the type of sales channel is a critical factor. We assumed that for certain types of goods, suppliers provide the goods and retailers provide a sales channel. Only through cooperation can the suppliers and retailers promote the goods and sell them to consumers. Regarding the selling of goods, cooperation between suppliers and retailers is effectively a form of partnership rather than a completely transaction-oriented relationship. In a retail sales channel, when a consumer purchases consigned goods from a retailer (the sales price is determined by the supplier), the retailer must immediately pay a consignment percentage to the supplier. The consignment percentage is stipulated in an advance pricing agreement between the retailer and the supplier. From the perspective of the retailer, the profits from consignment sales are regarded as rental income for providing a sales channel; however, such income is not paid periodically and the amount paid is not fixed. This situation is not only ongoing, but the level of income changes with the sales rate.

The aforementioned trading patterns raise the following three questions: In what type of industrial environment or under what policy is it appropriate for suppliers and retailers to form a partnership to enhance product sales collaboratively? Who should initiate or establish such partnerships? Who should supervise the partnership to ensure that the parties honor the contract, and who should monitor and control the supplier to ensure its stability? Addressing these three questions simultaneously requires considering the involved suppliers, retailers, and financial institutes.

Partnerships between suppliers and retailers are particularly crucial for developing Taiwan's industries. According to the statistics of the Small and Medium Enterprise

Administration (MOEA-SMEA) [1], 97.73% of all enterprises in Taiwan are small and medium-sized enterprises (SMEs). In the manufacturing sector as well as the wholesale and retail trade sector, 96.12% and 97.55% are SMEs, respectively. In this industrial environment, most enterprises in Taiwan are small and medium-sized enterprises that cannot provide sufficient collateral for bank loans. Consequently, economic development in Taiwan has effectively been restricted because the banks provide limited funds to assist enterprises in investment, research and development, and innovation. The aforementioned consignment model seems complex (involving both supplier and retailers), but the key is who supervises the retailer to ensure that they pay the agreed percentage immediately to the supplier in accordance with the advance pricing agreement? We recommend that such a transaction pattern be operated through the assistance of banking institutions or third party payment platforms, which has particular implications in Taiwan's retail industry.

From a supply chain perspective, the retailers' profit (the relationship between product price and cost) is closely related to that of their suppliers. Thus, the relationship between suppliers and retailers is increasingly being valued. A superior partnership can not only reduce uncertainties in the supply chain, but also enable retailers to play a crucial role in a successful supply chain system. In recent years, suppliers have shifted from employing their traditional policies (TPs) to adopting consignment policies (CPs). Such shifting has become a popular trend, in which suppliers cosign their goods to multiple retailers. The operation pattern of suppliers and retailers working individually has transformed into a pattern involving bilateral cooperation. This is a common consignment channel used by Watsons in Asia, 7–11 in the United States, Melissa and Doug, and numerous corner shops. The definition of consignment, according to the American Production and Inventory Control Society (APICS), is "the process of a supplier placing goods at a customer location without receiving payment until after the goods are used or sold."

The following are the advantages of consigning products to multiple retailers:

(a) The rent for the sales location and insurance costs are absorbed by the retailer.

(b) Reputable or trustworthy consignment retailers can be selected to establish long-term relationships.

(c) When popular sales locations change with the environment, suppliers can rapidly adjust sales locations to increase flexibility.

(d) Suppliers can increase the quantity of products on the shelves by consigning to multiple retailers, and the quantity of products available on shelves for viewing by consumers is an essential indicator in product visibility.

(e) Suppliers can understand the market distribution of products by using Electronic Data Interchange (EDI) to contact retailers.

(f) Suppliers can obtain real-time product sales reports from retailers, which enables suppliers to actively respond to changes in consumer product preferences.

(g) Suppliers can use advantageous inventory management and transportation strategies to maintain adequate supplies among retailers.

(h) It reduces suppliers' costs caused by obsolete products.

The advantages for retailers accepting supplier-consigned products are as follows:

(a) Reduces tied up inventory capital and improves cash flow.

(b) Reduces losses from returns and exchanges because of insufficient consumer awareness regarding product attributes, such as changes in product size, form, or color.

(c) Buyer (retailer) transaction costs (such as sellers delivering the products to the retail store) are absorbed by the sellers (main supplier).

(d) Retailers that use e-commerce platforms (Web-based transactions) for retail sales can guarantee that they transfer payment to suppliers only after consumers have received their products. Because e-commerce transaction methods use banks as a third party guarantor, transaction disputes as a result of insufficient consumer awareness toward product information can be reduced.

(e) Improves retailer service levels (reduces risk of being out of stock).

(f) The retailers can reduce the inventory cost of unsold goods resulting from changes in consumer preferences or from products having an extremely short life cycle. Moreover, the losses incurred from unsold goods can be reduced, and high-demand products or those that meet the needs of consumers can be made available for purchase within a relatively short time. Nonetheless, the effect of the cooperative consignment strategy is determined by the completeness of the consignment condition.

Over the past decade, numerous studies have been conducted on consignment stocks (CSs) and have made great contributions to integrating the supplier-buyer supply chain. These studies include Zavanella and Zanoni [2], Battini et al. [3], Srinivas and Rao [4], Yu et al. [5], Ben-Daya et al. [6], Hariga and Al-Ahmari [7], Sarkar [8], Singh et al. [9], Islam et al. [10], and Zahran and Jaber [11]. Studies have mainly considered the optimal consignment models regarding the whole supply chain or investigated the optimal consignment decisions from the perspectives of single suppliers or of retailers. However, they have rarely discussed the inventory risk costs in terms of which parties should absorb them (the supplier alone or both the supplier and the retailers). More importantly, most studies have overlooked the fact that retailers are competitors. Their competition is mainly reflected in the retail prices of their goods. How a retailer decides on optimal retail prices is closely related to the retailer's upper limit of the gross profit. Given Taiwan's industry background and the aforementioned reasons, the present study considers how a supplier's partial absorption of inventory costs affects the retail prices set by multiple suppliers with different market shares. This is the main characteristic of the mathematical model this study proposes, marking the major difference between this model and other CS models.

The rest of this paper is arranged as follows. Section 2 explores relevant studies on CS and highlights the characteristics of the proposed model and how it differs from other models. In Section 3, the symbols and assumptions of this model are defined. The mathematical model is described in Section 4, and sensitivity analyses are detailed in Section 5. Section 6 provides our conclusions and highlights the findings and their managerial implications.

2. Supply Chain Problems

Numerous studies have been conducted on supply chain problems between buyers and sellers. Goyal [12, 13] proposed the joint economics lot size (JELS) model for solving total cost minimization problems between suppliers and buyers. In their studies on the promotion of the JELS model, Goyal [14] and Goyal and Gupta [15] relaxed the assumed condition that suppliers use lot sales to improve the practicality of the model. However, these models all assumed that both suppliers and buyers were willing to accept this type of structured arrangement, which does not conform to actual practice.

In reality, the economic order quantity encountered by suppliers and retailers may be different. Thus, suppliers and retailers must negotiate product unit price and lot quantity. The aforementioned optimal arrangement from supplier and retailer negotiation is not the optimal arrangement for either the supplier or the retailer [16].

2.1. Single-Supplier, Single-Buyer. In a single-supplier, single-buyer integrated inventory model, Hill [17, 18] discovered (under the assumption that buyer demand and ordering frequency is known) that the average total cost per unit time in a supplier and buyer cooperative relationship is far lower than when both parties do not cooperate. Goyal [19] further considered the influence of limitations in transportation equipment volume on the integrated model. Other related research focused on relaxing the assumed conditions to improve the applicability of the integrated inventory model [20–22]. Valentini and Zavanella [23] described the advantages of consignment stock (CS) strategy. Suppliers can not only use the storage space of buyers, but also avoid temporary large quantity orders from buyers. This enables suppliers to conduct product management that is most advantageous to themselves. Buyers can also maintain a basic stock level and improve service levels (reduce risks of being out of stock).

Braglia and Zavanella [24] proposed a CS strategy analysis model for a single-supplier and single-buyer in an uncertain environment (delayed delivery and random market demand). Zanoni and Grubbstrom [25] promoted a model by Braglia and Zavanella [24], which considered the optimization of quantity transported, number of deliveries, and delayed deliveries. The CS analysis model developed by Srinivas and Rao [26] considered the contractual and crashing costs of lead time. In their CS analysis model, Persona et al. [27] considered the risks of obsolete products. Hill and Omar [28] compiled the aforementioned single-supplier, single-buyer integrated product inventory problems. Using CS as an example, they allowed different lot quantities for each purchase and proposed a solution [29]. Gümüş et al. [30] discussed the influence of consignment storage and supplier inventory management. Ru and Wang [31] and Hwang and Wan [32] compared the profits and losses of retailer-managed consignment and supplier-managed consignment. Wang et al. [33] proposed a consignment inventory model of deteriorating products for buyers with storage limitations. Islam and Hoque [34] considered the optimal consignment inventory strategy for product demand distribution.

These studies typically explored problems in a single-supplier, single-buyer inventory system, and these research results cannot be generalized to single-supplier, multiple-buyer inventory management problems. The primary reason for this limitation is the assumption that suppliers' production strategies are not influenced by buyers' purchase quantity. In reality, the buyers' purchase quantity not only influences the income of suppliers, but also influences production costs. This influence grows when a supplier encounters multiple buyers [35, 36]. However, a competitive relationship exists between buyers and they will use the product management strategies that are most advantageous to themselves [37].

2.2. Single-Supplier, Multiple-Buyer. Numerous single-supplier, multiple-buyer integrated inventory analysis models have been proposed; however, these integrated inventory models do not discuss consignment inventory problems [8, 38–46]. Yet, a few of the perspectives are noteworthy: Woo et al. [40] indicated that all suppliers and buyers are willing to establish EDI systems to reduce ordering costs. Furthermore, suppliers can grasp the real-time sales situation of buyers and modify their decision systems [16]. Siajadi et al. [47] discussed supplier product-transportation strategies and indicated that suppliers who transport products to multiple buyers obtain more profits than those who transport products to a single-buyer. This difference resulted from the fact that suppliers effectively establish transportation strategies and reduce transaction costs [48]. In their literature review, Chen and Sarker [46] underlined that the integrated model of integrated pricing and build to stock has gradually gained the attention of academia.

In a study on single-supplier, multiple-buyer integrated consignment inventory, Piplani and Viswanathan [49] developed a performance assessment model for traditional policy (TP) and consignment policy (CP). Srinivas and Rao [4, 50] used a genetic algorithm to develop a consignment inventory optimization model. Zavanella and Zanoni [2] built a single-supplier, multiple-buyer integrated product inventory model based on CS. Yu et al. [5] used a simulation method to compare the potential profits of suppliers who used TP and CP. They discovered that suppliers using CP obtained a higher profit than those who used TP. Battini et al. [3] developed a multi-echelon inventory system for a single-supplier and multiple buyers. Islam et al. [10] proposed a single-supplier, single–vendor, multiple-buyer product consignment inventory model and discovered that using CP increased the profits of consignment partners. Ben-Daya et al. [6] built a seller management consignment inventory model. Zahran and Jaber [11] further compared the profit differences among models adopting only TP or CP or integrated models adopted both at the supplier–vendor and vendor–retailer levels. Other studies on single-supplier, multiple-buyer CS management primarily relaxed assumption conditions to consider environmental limitations in actual practice, or included product demand distribution into the considerations [7–9, 51–54]. Sarker [55] categorizes the consignment inventory model by structural configuration of the systems, operational policies, component analyses, cost and profit, and several other standard measures.

However, the focus of these research models was the contribution of consignment inventory toward the overall supply chain or to discuss optimal decisions in consignment inventory from the perspective of suppliers or retailers. These studies overlooked the fact that retailers must frequently adjust sale prices and irregularly promote the sales of product combinations when they encounter market competition. Few previous studies on consignment models have not discussed complete consignment models, in which the supplier absorbs the risk cost to retailers for failing to sell products, as well as partial consignment models, in which both suppliers and retailers absorb a part of the risk cost. Thus, the use of previous integrated consignment inventory models on these practical applications is limited.

Additionally, retailers have a competitive relationship, especially in a maturing e-commerce environment. Neither a consignment inventory system that considers the optimal decision of various retailers nor consignment inventory decisions that include product demand distribution problems can reflect the order decisions of retailers in a competitive relationship. Discussing the order decisions of retailers from the perspective of market share rate is highly relevant to the market situation and can increase the applicability of the results.

The primary feature of the transaction model proposed in this paper is that financial institutions are given adequate control over the transactions between suppliers, retailers, and consumers. If the suppliers obtain bank funds in installments for production purposes in accordance with a loan plan and then supply goods to the retailers through a sales channel affiliated with the bank, then the bank can easily determine whether the conversion of loaned funds into goods is as planned. In addition, a portion of the profits generated through the sale of goods under the proposed model can contribute to ongoing loan repayments as per the agreement. Therefore, the three questions inferred from a partial consignment model are echoed: (1) In an industrial environment a high percentage of enterprises are SMEs or enterprises often cannot provide sufficient collateral to gain bank loans, (2) suppliers or financial institutes can take the initiative and propose partnerships between suppliers and retailers, and (3) financial institutes may play the role of supervisors to ensure that the partnership is carried out according to their contracts and that the supplier stably provides supplies. The main negotiation when the supplier and multiple retailers make a contract will lie in the ratio at which each party undertakes the inventory costs. The proposed model has attracted considerable attention from the business sector and banking industry in Taiwan. The primary purpose of this study is to promote the proposed transaction model at all social levels in Taiwan, thereby achieving a mutually beneficial outcome for all parties (suppliers, retailers, and the banking industry). This is also the main difference between the proposed model and past CS models.

This paper examined the suppliers consignment strategies based on the assumption that the retailers agree to a partial consignment transaction model. The model in this study is for a single-supplier consigning products to multiple retailers, and the pricing decision for a single product was considered. The decision makers for pricing can be divided into a single-supplier and multiple retailers. When the supplier deals with multiple retailers, each retailer adopts an economic order quantity (EOQ) decision model that minimizes each cycle's total cost (the sum of ordering costs and inventory costs) according to its market share (sales quantity per unit time). This study's mathematical model examines how, given that the supplier partially absorbs the inventory costs of the multiple retailers (i.e., the retailers only need to pay part of the wholesale price to the supplier when placing orders and can pay the rest after the retail sale is complete), the wholesale price and the partial absorption of inventory costs affect the retail prices of multiple retailers with different market shares.

3. Symbols and Assumptions

This study uses capitalized English characters to represent functions and lower case English characters to represent the constants.

p: the price at which suppliers sell products to retailers (the wholesale price), where $p > c > 0$.

c: cost per unit product obtained by suppliers.

e: the cost per unit the retailer immediately pays the supplier upon buying the product, where $p \geq e \geq 0$.

$$(p-e) \text{ is the remaining amount the retailers delay in paying the supplier until a product they have purchased is sold to the consumer.} \tag{1}$$

When $e = 0$, the supplier adopts the strategy of complete consignment: the retailers only pay the supplier after they finish selling the products to customers.

When $e < p$, the supplier adopts a partial consignment strategy. In that case, usually the supplier must pay rack fees in advance, such as a fixed amount of money or a certain percentage of the agreed sales price specified in a contract. When $e = p$ the supplier and retailers adopt the TP in which the retailers buy out the goods. In the complete consignment model, the risk cost of unsold goods is absorbed by the retailer, whereas that in the partial consignment model is absorbed by both the supplier and the retailer.

Because supplier adopting complete consignment model is a special case of this study, the general characteristics of this study results in the complete consignment model still hold.

a: the fixed transaction cost (i.e., the setup cost) of each retailer for each purchase (cost a is produced with each purchase regardless of purchase quantity).

s: the cost of ownership per unit capital in each unit time.

h: retailers' cost of ownership per unit product in each unit time can be assumed from (1):

$$h = e \cdot s. \tag{2}$$

n: number of retailers.

v_i: the ith retailers' gross profit for each unit product, that is, the difference between the retailers' retail price $(p + v_i)$ and purchase price p; v_i value is the retailers' decision variable, which differs with each retailer.

v_i^*: the gross profit of maximized unit time profit for retailer i.

$$\text{The optimized retail price for retailer } i \text{ is } \left(p + v_i^*\right). \tag{3}$$

θ_i: the market share of retailer i, where

$$0 < \theta_n \leq \theta_{n-1} \leq \cdots \leq \theta_1, \qquad \sum_{i=1}^{n} \theta_i = 1. \tag{4}$$

$\bar{r}$: the upper limit for consumer market demand rate (demand rate when sales price $(p + v_i)$ is 0).

R: sales rate per unit time (sales quantity per unit time) for retail price $(p + v_i)$, where

$$R\left(p + v_i\right) = \bar{r} - l\left(p + v_i\right), \quad i = 1, 2, \ldots, n. \tag{5}$$

l: the rate of change for sales price and unit time sales quantity in the consumer market, where $\bar{r}/l$ is the upper limit of the sales price in the consumer market. When the sales price $(p + v_i)$ increases to $\bar{r}/l$, the demand rate is 0 (as shown in (5)). Therefore,

$$\left(\frac{\bar{r}}{l} - p\right) \text{ is the upper limit for gross profit } v_i, \quad i = 1, 2, \ldots, n. \tag{6}$$

r_i: the sale quantity of retailer i per unit time. When the retail price is $(p + v_i)$, the retailer sales quantity per unit time (r_i) is the sales rate per unit time (R) (as shown in (5)) multiplied by the market share of retailer θ_i:

$$r_i = \theta_i \left[\bar{r} - l\left(p + v_i\right)\right]. \tag{7}$$

4. Mathematical Model

Providing that n retailers using EOQ purchase decision exist and that they all purchase from the same supplier, the situation encountered by each retailer is as follows.

4.1. Retailer's Optimal Purchase Cycle and Optimal Purchase Quantity. The optimal solution from the EOQ model showed that when the sales price of retailer i is $(p + v_i)$, the optimal purchase cycle t_i and the optimal purchase quantity q_i for each cycle are as follows [56]:

$$\begin{aligned} t_i &= \sqrt{\frac{2 \cdot a}{h \cdot r_i}} = \sqrt{\frac{2 \cdot a}{e \cdot s \cdot \theta_i \left[\bar{r} - l\left(p + v_i\right)\right]}}, \\ q_i &= \sqrt{\frac{2 \cdot a \cdot \theta_i \left[\bar{r} - l\left(p + v_i\right)\right]}{e \cdot s}}. \end{aligned} \tag{8}$$

4.2. The Maximal Unit Time Profit π_i of Retailer i. From (7), the unit time income of retailer i can be obtained:

$$\left(p + v_i\right) r_i = \left(p + v_i\right) \cdot \theta_i \left[\bar{r} - l\left(p + v_i\right)\right]. \tag{9}$$

From (7) and (8), when the gross profit for the ith retailer is v_i, the cost of ownership per unit inventory in each unit time for the retailer i is

$$\begin{aligned} &\frac{1}{t_i}\left\{a + p \cdot \theta_i \left[\bar{r} - l\left(p + v_i\right)\right] \cdot t_i + \frac{1}{2} es \cdot q_i t_i\right\} \\ &= \sqrt{\frac{es \cdot \theta_i \left[\bar{r} - l\left(p + v_i\right)\right]}{2a}} \cdot a + p \\ &\quad \cdot \theta_i \left[\bar{r} - l\left(p + v_i\right)\right] \\ &\quad + \frac{1}{2} es \sqrt{\frac{2a \cdot \theta_i \left[\bar{r} - l\left(p + v_i\right)\right]}{e \cdot s}} \\ &= \sqrt{2aes \cdot \theta_i \left[\bar{r} - l\left(p + v_i\right)\right]} + p \\ &\quad \cdot \theta_i \left[\bar{r} - l\left(p + v_i\right)\right]. \end{aligned} \tag{10}$$

From (10), when the values of p and e are given by the supplier, the maximal unit time profit π_i of retailer i is

$$\begin{aligned} \max_{0 \leq v_i \leq \bar{r}/l - p} \pi_i &= v_i \theta_i \left[\bar{r} - l\left(p + v_i\right)\right] \\ &\quad - \sqrt{2aes \cdot \theta_i \left[\bar{r} - l\left(p + v_i\right)\right]}, \\ & i = 1, 2, \ldots, n. \end{aligned} \tag{11}$$

4.3. Optimal Solution v_i of (11). Let v_i^* be the optimal solution for (11). Consider the derivative of π_i with respect to v_i to obtain

$$\begin{aligned}\frac{d\pi_i}{dv_i} &= \theta_i\left[\bar{r} - l\left(p + v_i\right)\right] - l\theta_i v_i + \sqrt{2aes\theta_i} \\ &\quad \cdot \frac{l}{2\sqrt{\bar{r} - l\left(p + v_i\right)}} \\ &= \frac{\theta_i}{\sqrt{\bar{r} - l\left(p + v_i\right)}}\left[F\left(v_i\right) + l\sqrt{\frac{aes}{2\theta_i}}\right], \\ &\quad 0 \le v_i \le \frac{\bar{r}}{l} - p,\end{aligned} \tag{12, 13}$$

where the function $F(v_i)$ is defined by

$$\begin{aligned}F\left(v_i\right) &= \left[\bar{r} - l\left(p + v_i\right)\right]^{3/2} - lv_i\left[\bar{r} - l\left(p + v_i\right)\right]^{1/2} \\ &= \left[\bar{r} - l\left(p + v_i\right)\right]^{1/2}\left[\bar{r} - l\left(p + 2v_i\right)\right], \\ &\quad 0 \le v_i \le \frac{\bar{r}}{l} - p.\end{aligned} \tag{14}$$

Calculating $F'(v_i)$ and $F''(v_i)$, it yields that

$$\begin{aligned}F'\left(v_i\right) &= \frac{-3}{2}l\left[\bar{r} - l\left(p + v_i\right)\right]^{1/2} - l\left[\bar{r} - l\left(p + v_i\right)\right]^{1/2} + \frac{l^2 v_i}{2}\left[\bar{r} - l\left(p + v_i\right)\right]^{-1/2} \\ &= \frac{l}{2\sqrt{\bar{r} - l\left(p + v_i\right)}}\left[lv_i - 5\left(\bar{r} - l\left(p + v_i\right)\right)\right] = \frac{3l^2}{\sqrt{\bar{r} - l\left(p + v_i\right)}}\left[v_i - \frac{5}{6}\left(\frac{\bar{r}}{l} - p\right)\right], \quad 0 \le v_i \le \frac{\bar{r}}{l} - p,\end{aligned} \tag{15}$$

$$\begin{aligned}F''\left(v_i\right) &= 3l^2\left(\frac{\sqrt{\bar{r} - l\left(p + v_i\right)} + \left[v_i - (5/6)\left(\bar{r}/l - p\right)\right] \cdot \left(l/2\sqrt{\bar{r} - l\left(p + v_i\right)}\right)}{\bar{r} - l\left(p + v_i\right)}\right) \\ &= 3l^3 \cdot \frac{2\left[\bar{r}/l - \left(p + v_i\right)\right] + \left[v_i - (5/6)\left(\bar{r}/l - p\right)\right]}{2\sqrt{\bar{r} - l\left(p + v_i\right)} \cdot \left[\bar{r} - l\left(p + v_i\right)\right]} = \frac{3l^2\left[(7/6)\left(\bar{r}/l - p\right) - v_i\right]}{2\sqrt{\bar{r} - l\left(p + v_i\right)} \cdot \left[\bar{r}/l - p - v_i\right]} > 0.\end{aligned} \tag{16}$$

Using $(d\pi_i/dv_i)|_{v=v_i^*} = 0$ and calculating (11) and (12), it yields that

$$\begin{aligned}\pi_i^* &= \pi_i\left(v_i^*\right) = 2\left[\frac{\bar{r} - l\left(p + v_i^*\right)}{l}\right]\left.\frac{d\pi_i}{dv_i}\right|_{v_i=v_i^*} + \pi_i\left(v_i^*\right) \\ &= \theta_i\left[\bar{r} - l\left(p + 2v_i^*\right)\right] \cdot 2 \cdot \frac{\bar{r} - l\left(p + v_i^*\right)}{l} \\ &\quad + v_i^*\theta_i\left[\bar{r} - l\left(p + v_i^*\right)\right] \\ &= \theta_i\left[\bar{r} - l\left(p + v_i^*\right)\right]\left[2\frac{\bar{r}}{l} - 2\left(p + 2v_i^*\right) + v_i^*\right] \\ &= 2\theta_i\left[\bar{r} - l\left(p + v_i^*\right)\right]\left[\frac{\bar{r}}{l} - p - \frac{3}{2}v_i^*\right]\end{aligned} \tag{17}$$

and hence

$$v_i^* < \frac{2}{3}\left(\frac{\bar{r}}{l} - p\right). \tag{18}$$

From (15), we can obtain

$$F'\left(v_i\right) < 0 \quad \text{if and only if } v_i < \frac{5}{6}\left(\frac{\bar{r}}{l} - p\right). \tag{19}$$

The diagram obtained from (13), (15), (16), and (18) is shown in Figure 1.

5. The Properties of Optimal Solution v_i^* of (11)

Eqs. (13) and (14) showed that v_i^* must satisfy

$$\begin{aligned}0 &= \left.\frac{d\pi_i}{dv_i}\right|_{v=v_i^*} = F\left(v_i^*\right) + l\sqrt{\frac{aes}{2\theta_i}} \\ &= \left[\bar{r} - l\left(p + v_i^*\right)\right]^{3/2} - lv_i^*\left[\bar{r} - l\left(p + v_i^*\right)\right]^{1/2} \\ &\quad + l\sqrt{\frac{aes}{2\theta_i}}\end{aligned} \tag{20}$$

and hence

$$0 = \lim_{e \to 0}\left[F\left(v_i^*\right) + l\sqrt{\frac{aes}{2\theta_i}}\right] = F\left(v_i^*\right). \tag{21}$$

This implies that

$$\lim_{e \to 0} v_i^* = \frac{1}{2}\left(\frac{\bar{r}}{p} - p\right) \quad \text{(c.f. Figure 1)}. \tag{22}$$

5.1. The Changing Effect of the Optimal Gross Profit v_i^* of Retailer i with respect to Price p. We viewed v_i^* as a function of p (parameters except for p remain unchanged) and

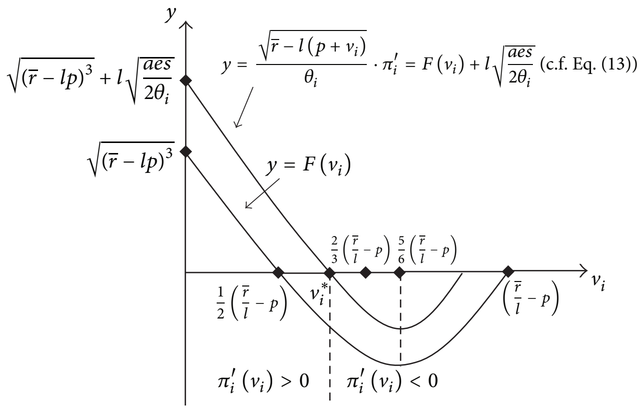

Figure 1: Optimal gross profit v_i^* of retailer i.

considered the partial differential of (20) with respect to p (denoted by $v_i^{*\prime}(p)$) to obtain

$$\begin{aligned} &\frac{-3}{2} l\left[\bar r - l\left(p + v_i^*\right)\right]^{1/2}\left[1 + v_i^{*\prime}(p)\right] \\ &\quad - l v_i^{*\prime}(p)\left[\bar r - l\left(p + v_i^*\right)\right]^{1/2} \\ &\quad - l v_i^* \frac{-l\left[1 + v_i^{*\prime}(p)\right]}{2\sqrt{\bar r - l\left(p + v_i^*\right)}} = 0; \end{aligned} \tag{23}$$

that is,

$$\begin{aligned} &-3l\left[\bar r - l\left(p + v_i^*\right)\right]\left[1 + v_i^{*\prime}(p)\right] \\ &\quad - 2l v_i^{*\prime}(p)\left[\bar r - l\left(p + v_i^*\right)\right] + l^2 v_i^*\left[1 + v_i^{*\prime}(p)\right] \\ &\quad = 0, \\ &0 = v_i^{*\prime}(p)\cdot 3l\left[\bar r - l\left(p + v_i^*\right)\right] + 2l\left[\bar r - l\left(p + v_i^*\right)\right] \\ &\quad - l^2 v_i^* = -3l\left[\bar r - l\left(p + v_i^*\right)\right] + l^2 v_i^*. \end{aligned} \tag{24}$$

This implies that

$$\begin{aligned} v_i^{*\prime}(p) &= \frac{-3\left[\bar r - l\left(p + v_i^*\right)\right] + l v_i^*}{5\left[\bar r - l\left(p + v_i^*\right)\right] - l v_i^*} \\ &= \frac{4v_i^* - 3\left(\bar r - lp\right)}{-6v_i^* - 5\left(\bar r - lp\right)} \\ &= \frac{4\left[(3/4)\left(\bar r/l - p\right) - v_i^*\right]}{6\left[(5/6)\left(\bar r/l - p\right) + v_i^*\right]}. \end{aligned} \tag{25}$$

Thus

$$v_i^{*\prime}(p) > 0 \quad \text{if and only if } v_i^* < \frac{3}{4}\left(\frac{\bar r}{l} - p\right). \tag{26}$$

It means that v_i^* is smaller than the gross profit upper limit $(\bar r/l - p)$ of 75%, $\forall i = 1, 2, \ldots, n$.

The upper limit of product gross profit refers to the phenomenon in which nobody is willing to purchase the products when retailers increase the unit price to $(\bar r - p)$. According to (26), the condition for individual retailers' optimal gross profit v_i^* to increase with the per unit purchase price p is that the current optimal gross profit v_i^* must be less than 75% of the aforementioned gross profit upper limit $(\bar r - p)$. Thus, an individual retailers' optimal gross profit v_i^* of less than 75% of the gross profit upper limit $(\bar r - p)$ and a greater distance between these two items lead to a greater increase rate $v_i^{*\prime}(p)$ in v_i^*. This rate increases with the per unit purchase price p.

5.2. The Changing Effect of v_i^* with respect to the Unit Product Prepayment e. The variable v_i^* is viewed as the function of e. Considering the partial differential of (20) with respect to e, it yields that

$$\begin{aligned} 0 = &\frac{-3}{2} l\left[\bar r - l\left(p + v_i^*\right)\right]^{1/2}\cdot v_i^{*\prime}(e) \\ &- l v_i^{*\prime}(e)\left[\bar r - l\left(p + v_i^*\right)\right]^{1/2} - l^2 v_i^* \\ &\cdot \frac{v_i^{*\prime}(p)}{2\sqrt{\bar r - l\left(p + v_i^*\right)}} + \frac{1}{2}\sqrt{\frac{as}{2\theta_i\cdot e}}, \\ &\qquad \forall i = 1, 2, \ldots, n. \end{aligned} \tag{27}$$

This implies that

$$\begin{aligned} &v_i^{*\prime}(e)\left(\frac{3}{2} l\left[\bar r - l\left(p + v_i^*\right)\right]^{1/2} + l\left[\bar r - l\left(p + v_i^*\right)\right]^{1/2}\right. \\ &\quad \left. + \frac{l^2 v_i^*}{2\sqrt{\bar r - l\left(p + v_i^*\right)}}\right) = \frac{1}{2}\sqrt{\frac{as}{2\theta_i\cdot e}}; \end{aligned} \tag{28}$$

that is,

$$\begin{aligned} &v_i^{*\prime}(e)\frac{1}{\sqrt{\bar r - l\left(p + v_i^*\right)}}\left(5\left[\bar r - l\left(p + v_i^*\right)\right] + l v_i^*\right) \\ &\quad = \frac{1}{l}\sqrt{\frac{as}{2\theta_i\cdot e}} \end{aligned} \tag{29}$$

and hence

$$\begin{aligned} v_i^{*\prime}(e) = &\left(5\left[\bar r - l\left(p + v_i^*\right)\right] + l v_i^*\right)^{-1} \\ &\cdot\sqrt{\left[\bar r - l\left(p + v_i^*\right)\right]}\cdot\frac{1}{l}\sqrt{\frac{as}{2\theta_i\cdot e}} > 0. \end{aligned} \tag{30}$$

This means that when e is reduced, v_i^* will decrease and therefore

$$\begin{aligned} &\frac{1}{2}\left(\frac{\bar r}{l} - p\right) = \lim_{e\to o^+} v_i^*(e) < v_i^*(e) < \lim_{e\to p^-} v_i^*(e) \\ &\qquad \text{(c.f. Eq. (30) and Figure 1)}. \end{aligned} \tag{31}$$

This equation shows that the optimal gross profit v_i^* of all individual retailers' increases with the advance payment of per unit purchase e; the increase rate (i.e., $v_i^{*\prime}(e)$) and various parameter value relationships are expressed in (30).

5.3. The Changing Effect of v_i^* with respect to the Retailer Market Share θ_i. When θ_i becomes smaller, the curve $y = f(v_i) + l\sqrt{aes/2\theta_i}$ in Figure 1 moves upward. Consequently, intersection v_i^* of the curve and the horizontal axis becomes larger. This indicates that

$$v_i^{*\prime}(\theta) < 0. \tag{32}$$

In reality, considering the partial differential of (20) with respect to θ, it yields

$$F'(v_i^*) \cdot v_i^{*\prime}(\theta) + l\sqrt{\frac{aes}{2}} \cdot \left(-\frac{1}{2}\right)\theta_i^{-3/2} = 0 \tag{33}$$

and hence

$$v_i^{*\prime}(\theta) = \frac{l\sqrt{aes}}{2F'(v_i^*)\sqrt{\theta^3}} < 0 \quad \left(\text{Figure 1 showed that } F'(v_i^*) < 0\right). \tag{34}$$

Together with (4), (32), and (34), it leads to

$$v_1^* \leq v_2^* \leq \cdots \leq v_n^*. \tag{35}$$

This indicated that retailers with high market share θ_i have low optimal retail price v_i^*.

5.4. The Changing Effect of v_i^* with respect to the Fixed Transaction Cost a. We viewed v_i^* in (20) as the function of parameters a (other parameters remain unchanged). Copying the discussion of (26), it leads to

$$v_i^{*\prime}(a) = \frac{\sqrt{es/(2\theta_i \cdot a)} \cdot \sqrt{\bar{r} - l(p + v_i^*)}}{5\sqrt{\bar{r} - l(p + v_i^*)} + lv_i^*} > 0. \tag{36}$$

This equation shows that the optimal gross profit v_i^* of any seller increases with its order preparation cost a. In other words, sellers must increase their selling price $(p + v_i^*)$ when retailers increase their order preparation cost a, resulting in an increase in sellers' optimal gross profit $v_i^*(a)$; the increase rate (i.e., $v_i^{*\prime}(a)$) is expressed in (36).

5.5. The Changing Effect of v_i^* with respect to the Interest s. We viewed v_i^* in (20) as a function of parameter s (other parameters remain unchanged). Copying the discussion of (26), it leads to

$$v_i^{*\prime}(s) = \frac{\sqrt{ae} \cdot \sqrt{\bar{r} - l(p + v_i^*)}}{\sqrt{2\theta_i \cdot s}\left[s\sqrt{\bar{r} - l(p + v_i^*)} + lv_i^*\right]} > 0. \tag{37}$$

This equation shows that when the retailers' holding cost s per unit time during the acquisition of unit funds (i.e., interest rate) increases, they must increase their selling price $(p + v_i^*)$. This causes their optimal gross profit v_i^* to increase with s; the increase rate (i.e., $v_i^{*\prime}(s)$) is expressed in (37).

5.6. The Changing Effect of v_i^* with respect to the Demand Rate Upper Limit $\bar{r}$. When $\bar{r}$ increases (other parameters remain unchanged), Figure 1 shows that the two curves in the diagram moved toward the upper level and, therefore, v_i^* increased. Considering the partial differential of (20) with respect to $\bar{r}$, it leads to

$$v_i^{*\prime}(\bar{r}) = \frac{3(\bar{r} - lp) - 4lv_i^*}{l[5(\bar{r} - lp) - 6lv_i^*]} > 0. \tag{38}$$

This equation shows that an increase in the upper limit of commodity market demand $\bar{r}$ causes the whole demand function curve of commodities to shift upward, which in turn increases the optimal gross profit $v_i^*(\bar{r})$ of any retail vendor. The increase rate of the optimal gross profit (i.e., $v_i^{*\prime}(\bar{r})$) is expressed in (38).

5.7. The Changing Effect of v_i^* with respect to the Demand Function Slope l. We viewed v_i^* in (20) as a function of parameter l. Considering the partial differential of (20) with respect to l, it yields

$$\begin{aligned} 0 = {} & \frac{3}{2}\sqrt{\bar{r} - l(p + v_i^*)} \cdot \left[-(p + v_i^*) - lv_i^{*\prime}\right] \\ & - \left(v_i^* + lv_i^{*\prime}\right)\sqrt{\bar{r} - l(p + v_i^*)} - \frac{1}{2}lv_i^* \\ & \cdot \frac{-(p + v_i^*) - lv_i^{*\prime}}{\sqrt{\bar{r} - l(p + v_i^*)}}. \end{aligned} \tag{39}$$

Multiplying the factor $\sqrt{\bar{r} - l(p + v_i^*)}$ to each term of the above equation, it leads to

$$\begin{aligned} & v_i^{*\prime}\left(\frac{5}{2}l[\bar{r} - l(p + v_i^*)] - \frac{1}{2}l^2 v_i^*\right) \\ & \quad = \frac{-3}{2}[\bar{r} - l(p + v_i^*)](p + v_i^*) \\ & \quad\quad - v_i^*\left[\bar{r} - \frac{3}{2} \cdot l(p + v_i^*)\right] \end{aligned} \tag{40}$$

and hence

$$\begin{aligned} & v_i^{*\prime} \cdot 5l\left[\bar{r} - l\left(p + \frac{6}{5}v_i^*\right)\right] \\ & \quad = -3[\bar{r} - l(p + v_i^*)](p + v_i^*) \\ & \quad\quad - v_i^*[2\bar{r} - 3l(p + v_i^*)] \\ & \quad = 6lv_i^{*2} + (9lp - 5\bar{r}v_i^*) - 3(\bar{r}p + lp^2). \end{aligned} \tag{41}$$

Since $5l[\bar{r} - l(p + (6/5)v_i^*)]$ is positive (c.f. Figure 1)

$$\begin{aligned} & v_i^{*\prime}(l) > 0 \\ & \text{if and only if } 6lv_i^{*2} + (9lp - 5\bar{r}v_i^*) - 3(\bar{r}p + lp^2) < 0. \end{aligned} \tag{42}$$

This implies that

$$v_i^{*\prime}(l) > 0$$

$$\text{if and only if } v_i^* > \frac{-\left(9lp - 5\bar{r}\right) + \sqrt{\left(9lp - 5\bar{r}\right)^2 + 72l\left(\bar{r}p - lp^2\right)}}{12l}. \quad (43)$$

This equation shows that when the absolute value of the negative slope for the commodity market demand function l ($l > 0$) increases, whether the retailers' optimal gross profit v_i^* increases should still be judged based on the relative values of other parameters. The judgment criteria are expressed in (43).

6. Conclusions

We represented the optimal retailer product pricing problem in supplier's partial absorption of retailer inventory costs into a mathematical model that can be specifically discussed. The optimal retail price in this model showed that regardless of the parameters in the model or the number of retailers, each retailer's optimal retail price was between 1/2 (50%) and 2/3 (66.67%) times that of the gross profit upper limit. This indicated the retail price margin selected by retailers does not exceed 16.67% times (that is, between 66.67% and 50%) that of the gross profit upper limit. In particular, the higher the market share is, the closer the optimal retail price is to 50% of the gross margin ceiling. In turn, optimal retail price of the lower market share is closer to 66.67% of the gross margin ceiling.

To expand the applicability of this model, we further demonstrated a rate of change mathematical model for the changes in optimal retail price caused by variations in each parameter, which yielded various properties. The results of this study showed that

(a) when a retailer sells goods, the lower the delayed payment that it pays the supplier, the closer the retailer's optimal gross profit to 2/3 of the gross profit's upper limit. By contrast, the higher the delayed payment, the closer the optimal gross profit to 1/2 of the optimal gross profit's upper limit.

(b) when retailers' purchase price increases for products that yield high gross profits (products that generate gross profits that exceed 75% of the gross profit upper limit) the optimal retail price decreases.

(c) when retailers' purchase price increases for products that yield low gross profits, the optimal retail price increases. The application of these results on the frequently encountered problem of whether retailers should increase or decrease retail prices when product purchase price increases has practical value.

Thus, comparisons of optimal retail prices for retailers with different market shares in this study are critical topics related to sales practices.

By using these research results, retailers can rapidly adjust product prices according to market change and sales requirements. Compared with complex analysis models previously used for calculating optimal policies, which are seldom used in actual practice [23], the results of this study are convenient to apply in actual practice. Furthermore, these results can help suppliers decide their wholesale price levels and establish levels for absorbing retailers' inventory costs. Future studies must further expand these research results.

Conflicts of Interest

The author declares that there are no financial or other conflicts of interest.

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Research Article

The Influence of 3D Printing on Global Container Multimodal Transport System

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Container multimodal transport system was an important promoter of postwar globalization. But in the future, part of global manufacturing may change from centralized to distributed due to 3D printing. To evaluate its impact, this research established a system dynamics model of sneakers supply chain firstly. The modeling showed that the total demand of international transport would decline after the application of 3D printing. For consumer country, the return of manufacturing would increase its container business. And that of producer country would reduce correspondingly. But for resource country, its resource exports would decline, while its container business may grow for the local processing of printing filaments. Secondly, the evaluations based on the data of Guangzhou port suggest that the 3D printing of sneakers was not enough to subvert the existing system. It would be broken only after the 3D printing of electrical products. By then, more manufacturing activities would transfer to the end of supply chain. On the other hand, producer country may actively respond to maintain its advantage in incumbent industrial pattern, such as Belt and Road initiative proposed by China. Deglobalization, caused by 3D printing, and globalization strengthening, caused by trade cooperation, will affect this system simultaneously.

1. Introduction

Container was one of the most important logistics inventions in the 20th Century. Levinson (2008) reviewed that this magic box was born in the United States (US) industrial booming after World War II. It was firstly applied in domestic coastal routes by Sea Land Company and Mattson Company and then quickly changed the traditional transport mode. Since 1960s, frequent trade activity between the United States and Europe has led to acceptance of this efficient logistics tool in most of European ports. With the Japanese product marketing in the western world in 1970s and the US Defense Department on the promotion of military containers in the Vietnam War, the initial Pacific Rim route US-Vietnam-Japan is gradually shaped. On the basis of the Atlantic and Pacific routes, container logistics has spread all over the world [1]. This simple box obviously shortens the loading-unloading time of the goods and compresses the transshipment links. In order to give full play to its potential, the International Standardization Organization (IMO) has developed a global size standard for it, which improves the efficiency of container logistics system and expands the scope of application of containers.

To fill up a huge container ship, the necessary labor force is very small, and the time required is only about half of that required for a small traditional ship to be loaded in 1960s. With containers, a small number of crew members can easily manage an ocean ship which is bigger than three football pitches. A driver can put down a trailer at the dock and then hang another one and drive away. He does not have to wait for the goods unloading from the container. Qingdao, Rotterdam, and other large ports have even realized the automatic loading and unloading of containers in the yard. That can reduce the interference of human factors. Transportation has become so efficient that freight costs will largely not have much impact on multinational production decisions.

Container can not only reduce transportation costs, but also save time. After combining the computer tracking management system into container, the multinational enterprises have developed the production mode of Just in Time (JIT) in the global scale. JIT was developed by Japanese car manufacturers firstly. And before container used, JIT was implemented only within the territory of Japan. Container realized the accuracy of the global flow of goods, significantly reducing the inventory of manufacturers and transshipment links. This promoted a longer supply chain so that buyers can safely place orders to the other side of the earth. The multimodal transport system based on container has combined ships, railways, and roads together to achieve global manufacturing and sales of goods.

Container transport has developed into a global scale, highly automated, and standardized industry today. For decades, container and a series of industrial modes derived from it have profoundly changed our world. In the international industry relayout, as container reduced the threshold of international logistics, the labor-intensive industries have gradually shifted from developed countries to developing ones with lower labor costs. After being manufactured in these countries, finished products were shipped all over the world by high-speed container liners. The global industry is evolving into a "resource-producer-consumer" pattern. The geographical distance between consumption and production is longer and longer. In order to maintain the competitiveness of producer countries in the international industrial layout, they are always upgrading their ports, highways, railways, and other container infrastructures, such as China, Korea, and ASEAN. Countries that lack container infrastructure are fixed as the role of the resource countries, such as Africa and South America. The infrastructures in these countries are more designed for the export of raw resources, such as crude oil pipe and minerals convey belt, rather than goods suitable for container shipment, such as semiproducts and finished products.

Upgrading a region's existing container infrastructure and conveyance requires a large amount of continued investment. This makes the current international industrial structure difficult to change in a short time. But that does not mean it is a permanent situation. We can review the case of digital camera that digital imaging technology rapidly and profoundly changed the way how people use camera. Some disruptive innovations, such as 3D printing (3DP), will probably break the existing supply chain mode. 3DP, or called additive manufacturing, is a digital manufacturing technology. Through a universal manufacturing machine, it can directly transform a digital file into a physical product. That means being free of customization and flexibility. It requires neither tools nor molds to produce the complex geometric structure. This also eliminates redundant assembly and reduces manual activities in the manufacturing process (Weller et al., 2015) [2]. It is drilling into the current system in some forms and gradually affecting the current container logistics. Then it may subvert the current global industrial division. The direction, velocity, and volume of global commodity flow may change dramatically.

Tien (2011) and Berman (2012) believed that 3DP and other digital technologies could combine together and let everyone participate in the manufacturing of goods through online platform [3, 4]. The main production paradigm would shift from the producer-centric mass production to the consumer-centric mass customization. Zeleny (2012) proposed that future manufacturing would not happen in the other side of the earth but around the consumers themselves. People could meet their material needs of daily work and life by using 3D printers and various printing materials, such as plastic filament and metal powder [5]. When 3DP has developed to this stage, the existing global industrial structure will be seriously impacted. While international container logistics system and globalization complement each other, globalization was derived from centralized production. Does centralized production transforming into distributed production mean that container will die out in the future?

2. Review of 3DP

3DP is a generic term for a variety of rapid prototyping technologies, such as Fused Deposition Modeling (FDM) and Stereo Lithography Apparatus (SLA) for plastic printing and Selective Laser Sintering (SLS) for metal printing. It was originally only for industrial product prototyping. In recent years, this technology has made a great breakthrough in the use of various materials. Industry began to use 3DP to make components and even finished products, but they have not formed scale yet. Now industry and academia are committed to explore its application of feasible models, both at the industrial level and at the personal level.

2.1. 3DP at Industrial and Personal Levels. In what circumstances will the factory executives choose 3DP? Scott and Harrison (2015) investigated and compared several factors in the manufacturing process, including total demand, factory operating cost, product variable cost, processing time, 3DP equipment efficiency, and printing filament cost. They found that total demand was a key factor in deciding whether to adopt 3DP, and the decline of filament cost would promote the 3DP application obviously [6]. Khajavi et al. (2015) put forward that the combination of 3DP and conventional process could greatly reduce the risk of new product sales. Firstly a batch of 3DP samples were thrown into the market. If successful, the mass production with conventional technology would follow. This proved that sometimes 3DP and conventional process would not substitute but complement each other [7]. On the other hand, 3DP is more suitable for the manufacturing of spare parts. Ruffo et al. (2007) proposed that the decision of enterprises to purchase or print small batches of spare parts depends on the cost, capacity, knowledge, response, and quality of 3DP. Integrated various factors, self-printing was better for spare parts replacement, rather than ordering out [8]. Sirichakwal and Conner (2016) summarized that the use of 3DP could achieve the virtual inventory. This helped to reduce the stock-out probability and inventory obsolescence of spare parts [9].

The above researches are more concentrated within the producers. But 3DP features will allow more consumers to participate in the manufacturing of products, called "prosumer." Cautela et al. (2014) proposed that the current personal applications of 3DP were mainly from direct E-commerce, alliances with established distributors, and specialized retail channels. The role difference among manufacturers, distributors, and consumers was becoming blurred increasingly [10]. In recent years, with the expiration of a variety of patent and the emergence of open source application, the threshold of 3DP continues to decline. For the economic analysis of 3DP in home applications, Wittbrodt et al. (2013) carried out an experiment. In a whole year the experimenters used RepRap, a kind of open source printer, to manufacture 20 kinds of products to meet their daily needs instead of going to shop. The results showed that this behavior saved a lot of money [11]. This allowed the users of 3DP to expand from enterprises to individual hobbyists and creative customers (Laplume et al., 2016) [12]. 3DP business has allowed consumers to take over more jobs from producers. The manufacturer-consumer decoupling point would shift to upstream more than in conventional ones. It could not only meet the personal requirements but also achieve a leaner and agiler supply chain.

2.2. 3DP and Global Supply Chain. The application of 3DP has blurred the boundary between producers and consumers. The ordinary production mode is evolving from centralized to distributed one. That will gradually be transmitted from domestic to international scope, thus affecting the current layout of global industries (Gress and Kalafsky, 2015) [13]. Laplume et al. (2016) believed that if 3DP gets more applications, a considerable part of the incumbent manufacturing activities would flow out from Asia back to Europe and US. Not only was 3DP closer to the consumption location, but also it could save more human activities, so that the comparative advantage of human cost in Asia was no longer obvious. Moreover, the local use of 3DP would save a large amount of import tariffs and bypass the technical barriers in some consumer countries. This in part offsets the current high cost of printing materials [12]. And as 3DP applications continue to expand, the cost of materials would slowly decline. That in turn would promote 3DP to be further accepted by the public.

From the perspective of logistics and supply chain, the use of 3DP will greatly reduce the material consumption during the manufacturing process. Global freight volume will decrease and logistics network will face strategic contraction. Chen (2016) pointed out that relevant countries should carry out feasible measures, such as the reform of logistics facilities and the cooperation with origin country of printing materials, to face the challenge brought by 3DP [14]. In the 3DP era, no complex JIT distribution and no complicated raw material or product category management existed. Global logistics scheduling would not be difficult any more. The conventional logistics providers must get transition to enhance their core competitiveness. Dong et al. (2016) analyzed the case of UPS Company and proved that a logistics servicer was transforming to a logistics manufacturer under the 3DP circumstance. In order to respond to customer demand quickly, logistics companies needed to change their inventory structure. In addition to regular goods, their distribution centers were also required to store a variety of printing materials for immediate production of the necessary order, to avoid shortages [15].

3. Research Idea

According to the above research, 3DP, which was originally used for prototyping only, is now developing into a mainstream way of manufacturing. At the industrial level, many companies are considering the combinations of 3DP and traditional process to shorten the product lead time. At the personal level, private users are attempting to make daily necessities by 3DP. The incumbent pattern will turn from centralized production to distributed one. Since 3DP can greatly reduce the traditional processes such as turning, milling and grinding, and the use of molds, the transportation of materials during the manufacturing process will decrease significantly. Traditional distribution servicers will be required to provide real-time print service of urgent goods.

At present, the mainstream 3DP material cost is relatively high. Its printing speed is also slow. This hinders the further popularization of this technology. But RepRap's case (Wittbrodt et al., 2013) showed that while consumers spent more on materials, they saved time and other costs to get goods [11]. In general, some niche goods with lower demand, especially personalized products and spare parts, are ideal for 3DP, which only needs to be produced of one or several unique pieces in a short time. Similarly, 3DP is also applied to some regular goods requiring to be more personalized, such as clothing, shoes, toys, and even houses. They have not become a scale yet. But their manufactures are constantly forging ahead. When 3DP matures, 3DP may be a powerful substitute of conventional process. Will the current industrial structure be affected? What about the evolution trend of global container multimodal transport system?

For different materials, the printing cost varies. For example, SLS for printing metals is quite expensive. The cost of printer and metal powder is many times that of conventional process. So it is generally used in the manufacturing of high-value components, such as aviation parts. In the short term, 3DP metal product is difficult to mass spread. Therefore, this research is more inclined to study the plastic resin product, which is cheaper and more mature.

3DP is more suitable to manufacturing the goods made of a single material. In recent years, with consumer demand for personalized products, they have become less satisfied with the regular styles of sneakers. Nike, Adidas, New Balance, and other transnational sports giants have been committed to the development of 3DP sneakers. These products are usually made of one or a few types of artificial plastics and their printing technology is FDM or SLA. Customers provided their foot size to the sneaker manufacturer and finally received their orders by real-time 3DP through the distributors. Because it was customized, the price was relatively high. And these orders have not been commissioned to the oversea foundry but the local 3DP workshop. The 3DP sneakers' accuracy is OK, but the speed and cost cannot match the requirements of mass production yet. This model is more like concept marketing and not so popular among the ordinary people.

In 2017, Carbon, which was a start-up company in Silicon Valley, cooperated with Adidas Company and developed the Continuous Liquid Interface Production (CLIP) technology to optimize the process of sneakers in collaboration with sports manufacturers. It could reduce the printing time of sneakers from 1.5 hours to 20 minutes. This greatly improved the productivity of 3DP sneakers. Adidas hoped to sell 5,000 pairs in 2017. And the annual sales volume could expand to 100,000 pairs in the future when the production times were shortened (Vincent, 2017) [16]. This is only a small amount compared to Adidas's annual sales of 100,000,000 pairs, but with the further development of 3DP technology and the promotion of consumer personalized requirement, sneakers may be the first product which are 3DP mass-customized in the foreseeable future. Therefore, this research focuses on the supply chain of 3DP sneakers.

3DP has not been large scale applied. The relevant data is lacking. Moreover, most of the existing achievements have focused on domestic scope. There is less quantitative research on the worldwide range. In order to evaluate the impact of 3DP on container multimodal transport system, it is necessary to analyze the evolution of transnational supply chain. Based on the case of 3DP sneakers, this research intends to establish a system dynamics model and then simulate possible scenarios and discuss the evolution of supply chain under these circumstances. Finally, the impacts of 3DP on the system are discussed based on the throughput data from a typical port in producer country.

System dynamics is a systematic simulation method to analyze the problems of production and inventory management. It is common in supply chain construction. Under the premise of insufficient data, the method can still predict conditional target variables by using flow diagrams which containing causal loops. Moreover, the flow diagram structure can intuitively reflect the operation process of the chain. Currently, 3DP related data is lacking. Therefore, system dynamics is viable to quantify the impact of 3DP on container multimodal transport system.

4. Modeling of the Sneakers Supply Chain

4.1. Traditional Supply Chain Model. The first step is to model the transnational supply chain of traditional sneakers. According to recent years' public data from Nike Company, it has 25% of employees and 10% of sales in China. In North America, it has about 1% of employees, but sales account for 50%. In the Middle East, Russia, and other oil origin regions, the number of employees is 1%, and the sales are only about 5%. There is no doubt that, in the Nike sneakers industry chain, China is a producer country, US is a consumer country, and the Middle East plays the role of a resource region. Set the starting point of the chain as an oil field in the Middle East. Its production of oil is shipped to China and refined to form raw plastic and then processed into sneakers. Ultimately these finished products are shipped to US, China, and the Middle East for sale. Since the research is concerned more with the transnational changes of material transportation, the domestic distribution part is not the focus. Therefore, the local sneakers distribution centers in these three regions are set to be the supply chain terminals.

In the model setting the sneakers are made of one single plastic. The main steps of the whole supply chain are as follows.

Table 1: Variable symbol of transnational supply chain.

Symbol	Meaning of variables
OfME	An oil field in the Middle East
ReBG	A refinery around the Beibu Gulf
PoPR	A port in the Pearl River Delta
DcPR	A distribution centre in the Pearl River Delta
PoPG	A port in the Persian Gulf
PfPR	A plastic processing factory in the Pearl River Delta
PoWU	A port in the West US
DcUS	A distribution centre in the US
PoBG	A port in the Beibu Gulf
MfPR	A sneaker manufacturing factory in the Pearl River Delta
DcME	A distribution centre in the Middle East

(1) The crude is exploited from the oil field in the Middle East and transported to the depot of the Persian Gulf by pipeline.

(2) The crude is loaded on a tanker and goes to the Beibu Gulf in China, which is a petrochemical industry cluster. In a refinery in the Beibu Gulf, the crude is processed into raw plastic and then shipped by trailer to a plastic processing factory in the nearby Pearl River Delta, a main manufacturing cluster in China.

(3) The raw plastic is transformed into plastic particles, which is the basic material for many plastic products.

(4) A foundry there receives the order from Nike headquarter and purchases these required plastic particles for production. In this process, its transport vehicle is still trailer. Through the injection molding, cutting, sewing, and other processes, the sneakers are completely made.

(5) The finished products for US and the Middle East will be shipped out through a port in the Pearl River Delta. The sneakers destined for US will go to one of the western coastal ports and then to the local distribution center by road. The sneakers destined for the Middle East will arrive at a port in the Persian Gulf and then also to the local distribution center by road. The sneakers for China are directly transported from the foundry to the local distribution center by domestic road.

The model is established by the VENSIM PLE software. The variable meaning in the model is shown in Table 1.

Based on the descriptions that is shown in Table 1, the system dynamics model of traditional supply chain is shown in Figure 1. The supply chain in this scenario is called *Scenario T*.

The focus of this research is to evaluate the impact of 3DP on the container transport system. The parameter setting is concerned more with the differences among various kinds of vehicle but does not pay much attention to storage. In addition, the shortest length of the supply chain under different circumstances needs to be determined. That means that all the goods should not stay long at any node. After

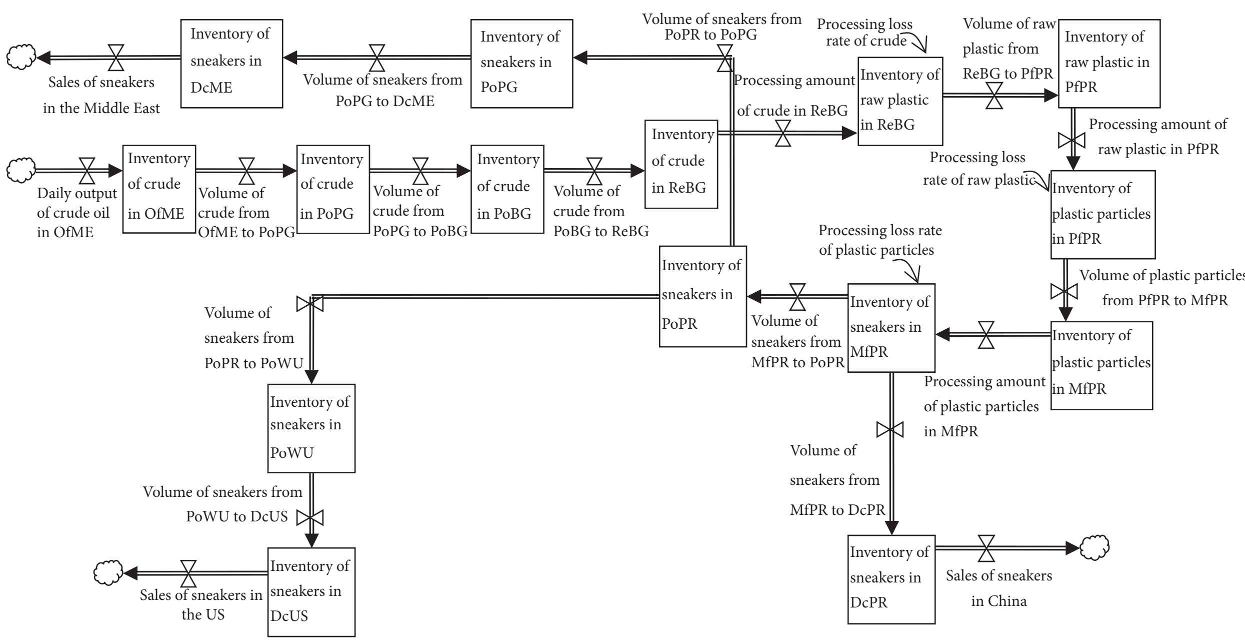

Figure 1: Flow diagram of supply chain in Scenario T.

Table 2: Setting of parameters in Scenario T.

Route	Transport mode and time spent
OfME-PoPG	3 days by pipeline
PoBG-ReBG	1 day by pipeline
PfPR-MfPR	1 day by trailer
PoPR-PoPG	12 days by container vessel
PoPR-PoWU	10 days by container vessel
MfPR-DcPR	2 days by trailer
PoPG-PoBG	15 days by tanker
ReBG-PfPR	1 day by trailer
MfPR-PoPR	1 day by trailer
PoPG-DcME	2 days by trailer
PoWU-DcUS	2 days by trailer
Time spent at each node	The crude is loaded or unloaded at the port for 3 days. The rest of the goods are finished for about 1 day

the goods are ready for shipment they cannot remain in the same node for more than one day. According to the above setting, referring to actual geographical and transport data, the transportation mode and their time spent are shown in Table 2.

This is set to be a supply and demand equilibrium model. When the model runs, no excess inventory is in any node of the chain. Based on the sales data of Nike Company, 20 tons of the sneakers is sold per day in the three regions, including 15 tons sold in US, 4 tons in China, and 1 ton in the Middle East. According to field investigation data, the conversion rate of crude into raw plastic is 33.33%. The conversion rate of raw plastic into plastic particles is 95.4%. In the shoemaking process, there is some wastage such as leftover bits and pieces. And the conversion rate of plastic particles into sneakers is 87.5%. In the circumstance of balanced supply and demand, the oil field in the Middle East produces 72 tons of crude per day to manufacture sneakers. Input the above data into the model and run the model simulation for 365 days. The result is shown in Table 3.

4.2. Future Scenarios and Matching Models. If the sneakers realize the 3DP production, the incumbent process will be completely overturned. The manufacturing activity in China will shift closer to the end consumer. Some studies have shown that consumers may choose to print the personal items at home, but the factory and workshop can provide the 3DP product with higher quality. That is because 3DP requires necessary postprocesses according to current technology. Nonprofessional consumer, if not able to cope, will reduce their experience. So it became complex to determine proper 3DP locations in the supply chain (Bogers et al., 2016) [17]. Sneakers are with a certain technical content. If printed by consumer themselves, they are not as good as from professional enterprises. Zeltmann et al. (2016) found that if 3DP was performed in a decentralized environment such as being homemade, there was risk of strength and durability in the finished product due to lack of qualified inspection [18]. The case of UPS Company (Dong et al., 2016) showed that in the 3DP era distribution provider is fully capable of acting as a qualified end-manufacturer [15]. Therefore, this model assumes the printing behavior of sneakers conducted in the local distribution centers of US, China, and the Middle East. The distribution centers get authorized and technical support from Nike Company. When they receive orders, they will print and deliver the product immediately. On the other hand, as a result of the shale gas revolution in recent years,

Table 3: Simulation results of freight volume and period in Scenario T.

Region	Bulk freight by land	Container freight by land	Bulk port throughput	Container port throughput	Starting sales time of sneakers
Middle East	26136 tons	317 tons	25848 tons	317 tons	The 50th day
US	0 tons	4785 tons	0 tons	4785 tons	The 48th day
China	24696 tons	22437 tons	24624 tons	5280 tons	The 35th day

Maritime route	Bulk freight	Container freight
Middle East-US	0 tons	0 tons
US-China	0 tons	4950 tons
China-Middle East	25776 tons	330 tons

Table 4: Newly added variable symbol of transnational supply chain in Scenario 1.

Symbol	Meaning of variables
PoGM	A port in the Gulf of Mexico
ReGM	A refinery around the Gulf of Mexico
PfUS	A plastic processing factory in US

US is likely to achieve self-sufficiency in the supply of crude. This means that the origin of crude is no more limited to the Middle East. Taking account of these possibilities, this research designed three extreme scenarios, called Scenario 1, Scenario 2, and Scenario 3. Among them, the origin of crude, the processing location of printing materials, and the region where sneakers are manufactured will change. The actual supply chain evolution may occur in the range among the three scenarios.

4.2.1. Simulation of Scenario 1. In Scenario 1, the origin of crude is still the Middle East. The materials used to make sneakers are no longer plastic particles, but special filaments for 3DP. Its production process is similar to plastic particles, which are manufactured by raw material in a processing factory. Since US and China have conducted a lot of investments in the research and development of 3DP for many years, such as "National Strategic Plan for Advanced Manufacturing" (2012) and "National Network for Manufacturing Innovation" (2012) in US and "Made in China 2025" (2015) and "National promoting plan of additive manufacturing" (2015) in China, this scenario sets that the locations of filament production are in US and China, respectively. The filaments made in US are for the sneakers of US consumers. And the filaments made in China are for the sneakers of China and the Middle East consumers. The crude for filament production is all from the Middle East. In Scenario 1, US is not only a consumer country, but also a filament producer. And its major crude unloading port and refinery cluster are around the Gulf of Mexico. Thus three new nodes are added. Their symbols are shown in Table 4.

In Scenario 1, the main steps of the whole supply chain have changed as follows.

(1) The crude is exploited from the oil field in the Middle East and transported by pipeline to the depot in the Persian Gulf.

(2) Different from Scenario T, the crude traffic is divided into two parts. One part is shipped to a port in the Gulf of Mexico and then refined to raw plastic and shipped by trailer to a plastic processing factory in US. The other is shipped to a port in the Beibu Gulf, also refined to raw plastic, and shipped by trailer to a plastic processing factory in the Pearl River Delta.

(3) The raw plastic is transformed into plastic filaments, which is the basic material for the 3DP of plastic. The model sets that the shipping way of filaments is container, no matter the container trailer by road or the container vessel by sea.

(4) Filaments made in US are shipped by trailer to a US distribution center. Filaments made in China are shipped to the distribution center in China by trailer and to the distribution center in the Middle East by container vessel, respectively.

(5) Nike headquarter informs the distribution centers to print and sends the sneakers in real time to the customers.

According to the above settings, the model is modified as shown in Figure 2.

Sneakers are not made in a shoe factory but printed directly in a distribution center. So the goods stay for 2 days at the distribution center, including printing and sorting, 1 day longer than that of Scenario T. The time spent in the newly added nodes is adjusted according to the actual investigated data. The remaining parameters of Scenario 1 are the same as those of Scenario T. Therefore, the transportation mode and their time spent are modified and shown in Table 5.

The sales per day of Scenario 1 are set the same as the one of Scenario T, 15 tons in US, 4 tons in China, and 1 ton in the Middle East. All kinds of materials have the same conversion rate in US and China. The conversion rate of crude into raw plastic is 33.33%. The conversion rate of raw plastic into plastic filaments is 93.8%. As the sneakers are made by 3DP, the loss is greatly reduced to negligible extent. The model sets that the conversion rate of filaments into sneakers is 100%. According to the setting, the crude shipped to US is 48 tons per day and generates 15 tons of filaments to the US distribution center. The crude shipped to China is 16 tons per day and generates 5 tons of filaments, in which 4 tons is shipped to China distribution center and 1 ton is shipped to

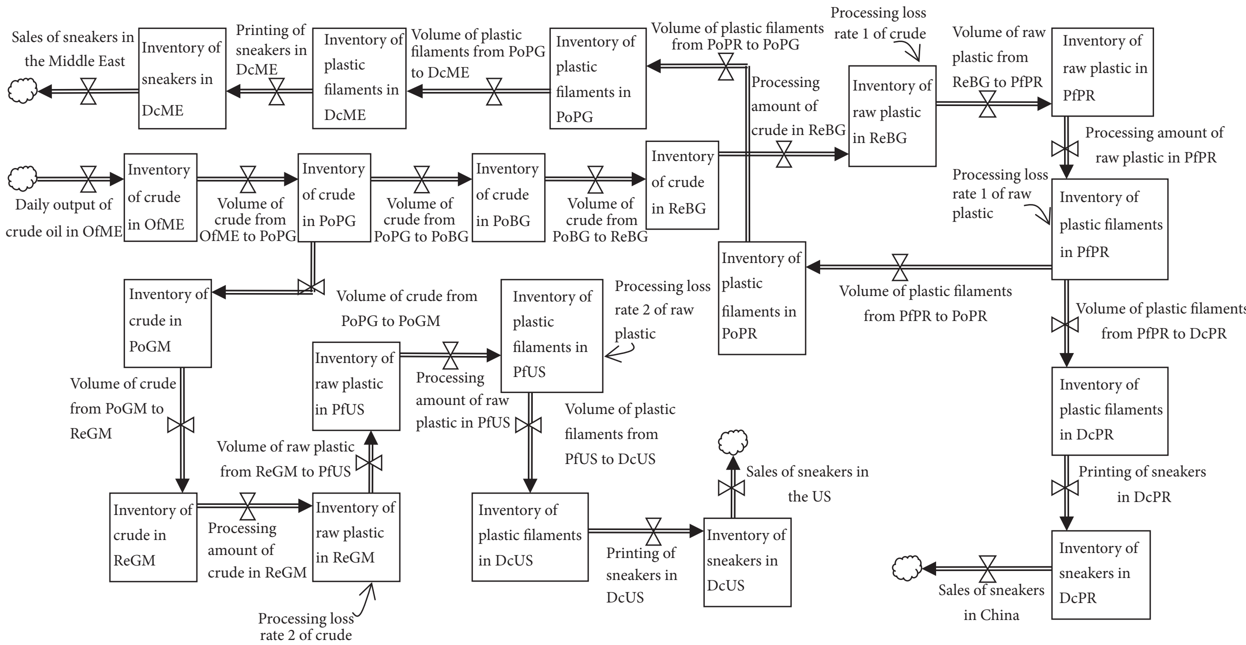

Figure 2: Flow diagram of supply chain in Scenario 1.

Table 5: Newly added setting of parameters in Scenario 1.

Route	Transport mode and time spent
PoGM-ReGM	2 days by pipeline
PfUS-DcUS	2 days by trailer
PfPR-DcPR	2 days by trailer
PoPG-PoGM	37 days by tanker
ReGM-PfUS	1 day by trailer
PfPR-PoPR	1 day by trailer
Time spent in each distribution center	2 days

the Middle East one. Input the above data into the model and run the model simulation for 365 days. The result is shown in Table 6.

4.2.2. Simulation of Scenario 2. Unlike Europe, US has gradually shifted from a typical crude consumer to a major producer because of the shale gas revolution in recent years. In Scenario 2, there are 2 origins of crude, the Middle East and US. The filaments used in China and the Middle East are processed by the crude from the Middle East. The filaments made in US are processed by the crude from US. The US origin area is still set around the Gulf of Mexico. Thus, add one new node into the Scenario model, an oil field in the Gulf of Mexico. Its symbol is OfGM. The crude oil passes through the pipeline to the nearby refinery, with a time spent of 2 days. Other settings remain the same as Scenario 1. The model is modified as shown in Figure 3.

The sales per day of Scenario 2 are set the same as the one of Scenario T, 15 tons in US, 4 tons in China, and 1 ton in the Middle East. The Middle East produces 16 tons of crude per day and ships it to China for manufacturing sneakers, while US produces 48 tons of crude per day locally. The other parameters of Scenario 2 and Scenario 1 are the same. Input the above data into the model and run the model simulation for 365 days. The result is shown in Table 7.

4.2.3. Simulation of Scenario 3. These years many regions have increased investment in the research and development of 3DP, including some countries in the Middle East. For example, Dubai, UAE, planned to build the whole nation into a global hub for 3DP by 2030. It majored in the industries of construction, medical products, and consumer goods. A market research institute, Future Market Insights, released a report (2016) predicting that from 2015 to 2025 the 3DP materials market in the Middle East will grow 16.7% per year [19]. In the foreseeable future some Middle East countries will probably get rid of the roles of resource country and be able to utilize 3DP technology to participate the international manufacturing more actively. Therefore, in Scenario 3 the Middle East will not export crude but process it into filaments and then export. In this case, in the Middle East the crude exploited from the oil field is firstly sent to a nearby refinery to transform into raw plastic. Then the raw plastic is transport by trailer to a plastic processing factory to produce filaments. Part of the filaments is shipped to the distribution center for local sneakers printing. The rest are shipped to Pearl River Delta port through the Persian Gulf port and finally reach a distribution center of China, which is used to make sneakers for Chinese customers. Add two new nodes to the model of Scenario 2. The settings of US remain the same. Their symbols are shown in Table 8.

The time spent in the newly added nodes is adjusted according to the actual investigated data. The remaining parameters of Scenario 3 are the same as those of Scenario 2.

Table 6: Simulation results of freight volume and period in Scenario 1.

Region	Bulk freight by land	Container freight by land	Bulk port throughput	Container port throughput	Starting sales time of sneakers
Middle East	23232 tons	319 tons	22976 tons	321 tons	The 49th day
US	15408 tons	9751 tons	15408 tons	0 tons	The 57th day
China	5488 tons	3487 tons	5472 tons	334 tons	The 36th day

Maritime route	Bulk freight	Container freight
Middle East-US	17184 tons	0 tons
US-China	0 tons	0 tons
China-Middle East	5728 tons	334 tons

Table 7: Simulation results of freight volume and period in Scenario 2.

Region	Bulk freight by land	Container freight by land	Bulk port throughput	Container port throughput	Starting sales time of sneakers
Middle East	5808 tons	321 tons	5744 tons	321 tons	The 51st day
US	17424 tons	11038 tons	0 tons	0 tons	The 16th day
China	5488 tons	3487 tons	5472 tons	334 tons	The 36th day

Maritime route	Bulk freight	Container freight
Middle East-US	0 tons	0 tons
US-China	0 tons	0 tons
China-Middle East	5728 tons	334 tons

Table 8: Newly added variable symbol of transnational supply chain in Scenario 3.

Symbol	Meaning of variables
ReME	A refinery in the Middle East
PfME	A plastic processing factory in the Middle East

Table 9: Newly added setting of parameters in Scenario 3.

Route	Transport mode and time spent
OfME-ReME	2 days by pipeline
PfME-DcME	1 day by trailer
PoPG-PoPR	12 days by container vessel
ReME-PfME	1 day by trailer
PfME-PoPG	2 days by trailer

Therefore, the transportation mode and their time spent are modified and shown in Table 9.

According to the above, the model is modified as shown in Figure 4.

The sales per day of Scenario 3 are set the same as the one of Scenario T, 15 tons in US, 4 tons in China, and 1 ton in the Middle East. The Middle East produces 16 tons of crude per day and ships it to China for manufacturing sneakers, while US produces 48 tons of crude per day locally. The other parameters of Scenario 3 and Scenario 2 are the same. Input the above data into the model and run the model simulation for 365 days. The result is shown in Table 10.

5. Simulation Result Analysis

In each scenario, there are two major transport ways in supply chain. The first one is bulk transport for crude, no matter by pipeline or tanker. The second one is container transport for semiproducts and finished plastic products, by vessel and trailer. According to Tables 3, 6, 7, and 10, Table 11 is established for comparing the simulation of four scenarios.

5.1. Flow Direction. For crude transportation, in Scenario 1 one part of crude is exported to US for filaments processing. This has facilitated the material flow within US territory and increased its port throughput. China's crude traffic is correspondingly reduced. But the Middle East remains the only resource exporter. In Scenario 2, US uses its own crude to process filaments. The oil of the Middle East is all exported to China. In Scenario 3, the Middle East enterprises made crude oil into filaments and then exported. The flow of crude only existed in the pipeline from oil fields to refineries. This proves that the 3DP distributed production will greatly shorten the global flow distance of primary raw materials. The unit freight turnover of primary raw materials will be significantly reduced.

For container transportation, Scenario 1 and Scenario 2 show that all semiproduct and finished plastic products of US circulate within the US territory. This will lead to the useless marine containers because of the non-trans-ocean transport. In the case of only domestic transport, it is likely that logistics providers are not willing to use container trailers but ordinary van to complete it, which has a more flexible demand response. In Scenario 3, the Middle East has become

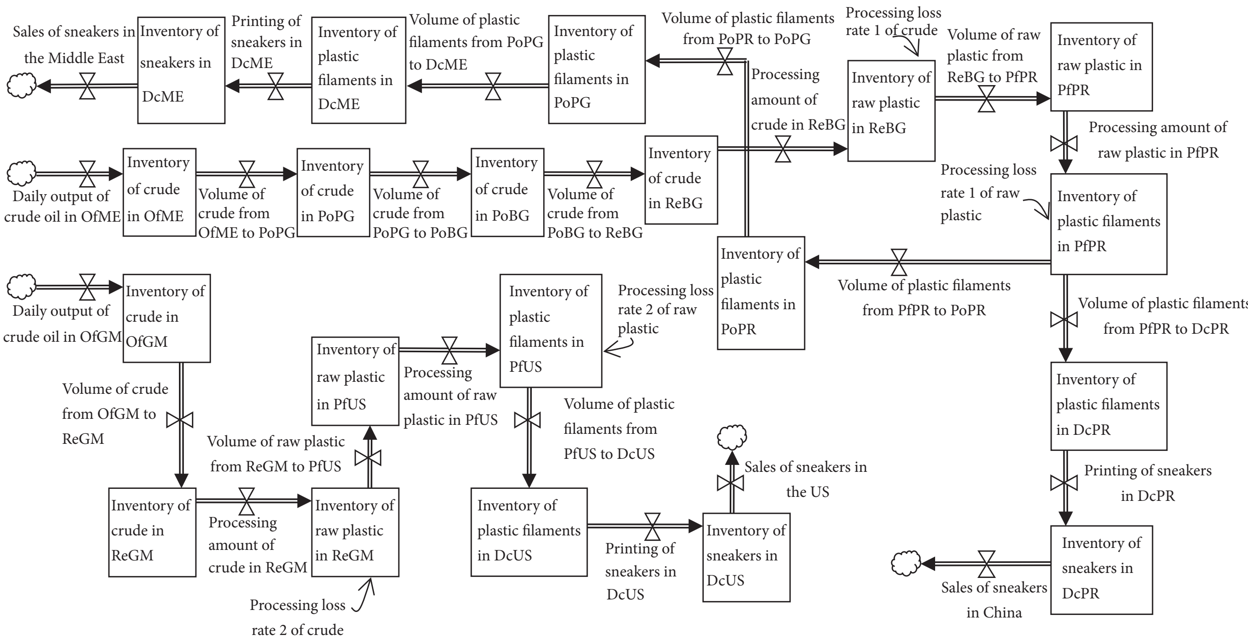

Figure 3: Flow diagram of supply chain in Scenario 2.

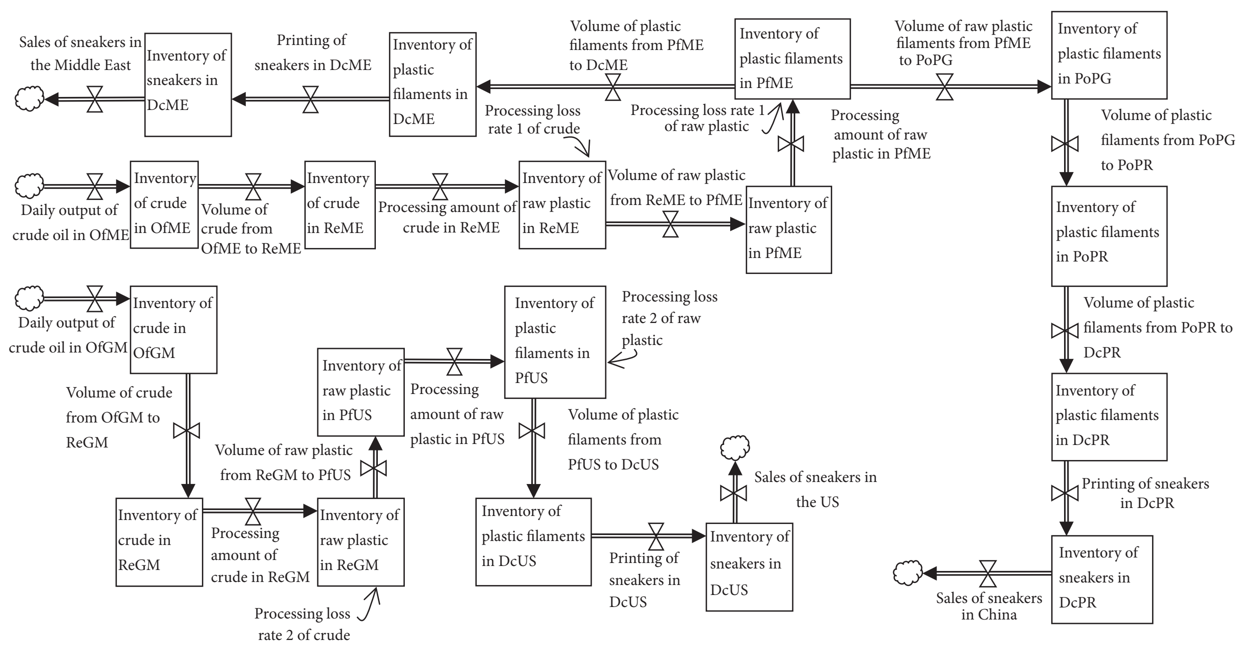

Figure 4: Flow diagram of supply chain in Scenario 3.

the exporter of filaments but not the importing region of sneakers. The container goods do not flow from China to the Middle East but in the opposite direction. On the one hand, the application of 3DP makes the countries which have both resource and consumer characteristics tend to circulate the business in domestic range. While container is more suitable for international multimodal transport, their use will decline if there is only domestic demand. On the other hand, the use of container in nonresource country can be maintained, because the transoceanic container of printing filaments is an efficient and punctual way to provide quick response to the demand of consumers in this digital era.

5.2. Flow Velocity. The faster the flow velocity, the shorter the start sales time of sneakers. In Scenario T, materials need to be transferred among multiple nodes and applied by several procedures. After 3DP application, the filaments generated by crude can be directly transported to the distribution center and printed according to the customer's order. The part of foundry manufacturing can be omitted, and there is no need

Table 10: Simulation results of freight volume and period in Scenario 3.

Region	Bulk freight by land	Container freight by land	Bulk port throughput	Container port throughput	Starting sales time of sneakers
Middle East	5808 tons	2263 tons	0 tons	1404 tons	The 16th day
US	17424 tons	11038 tons	0 tons	0 tons	The 16th day
China	0 tons	1352 tons	0 tons	1352 tons	The 34th day
Maritime route		Bulk freight		Container freight	
Middle East-US		0 tons		0 tons	
US-China		0 tons		0 tons	
China-Middle East		0 tons		1404 tons	

Table 11: Comparison of simulation data of four scenarios.

Region	The volume of different transport modes in different locations	Scenario T	Scenario 1	Scenario 2	Scenario 3
Middle East	Bulk freight by land	26136 tons	23232 tons	5808 tons	5808 tons
	Container freight by land	317 tons	319 tons	321 tons	2263 tons
	Bulk port throughput	25848 tons	22976 tons	5744 tons	0 tons
	Container port throughput	317 tons	321 tons	321 tons	1404 tons
	Start sales time of sneakers	The 50th day	The 49th day	The 51st day	The 16th day
US	Bulk freight by land	0 tons	15408 tons	17424 tons	17424 tons
	Container freight by land	4785 tons	9751 tons	11038 tons	11038 tons
	Bulk port throughput	0 tons	15408 tons	0 tons	0 tons
	Container port throughput	4785 tons	0 tons	0 tons	0 tons
	Start sales time of sneakers	The 48th day	The 57th day	The 16th day	The 16th day
China	Bulk freight by land	24696 tons	5488 tons	5488 tons	0 tons
	Container freight by land	22437 tons	3487 tons	3487 tons	1352 tons
	Bulk port throughput	24624 tons	5472 tons	5472 tons	0 tons
	Container port throughput	5280 tons	334 tons	334 tons	1352 tons
	Start sales time of sneakers	The 35th day	The 36th day	The 36th day	The 34th day
Middle East-US	Bulk freight	0 tons	17184 tons	0 tons	0 tons
	Container freight	0 tons	0 tons	0 tons	0 tons
US-China	Bulk freight	0 tons	0 tons	0 tons	0 tons
	Container freight	4950 tons	0 tons	0 tons	0 tons
Middle East-China	Bulk freight	25776 tons	5728 tons	5728 tons	0 tons
	Container freight	330 tons	334 tons	334 tons	1404 tons

to prepare the corresponding mold. It seems that the simplification of the process reduces the response time and improves the flow velocity. Although the printing speed of a single printer was still slower than that of the conventional process, some enterprises began to solve the problem. For example, Voodoo Manufacturing Company set up a printer group called Project Skywalker. They designed software to connect several to hundreds of ordinary FDM printers and even mechanical arms or other automation equipment together, just like "robot factory." These 3DP systems or groups could print large numbers of individual components and achieve mass production while maintaining the technical advantages of 3DP (3ders.org) [20]. The same way, of course, can also be applied to athletic footwear manufacturing. Moreover, with the application of CLIP or later the introduction of new technologies, the printing speed of sneakers can fully meet the requirements of mass production. Therefore, the shortcoming of 3DP speed will not delay start sales time any more.

However, the flow velocities of all regions do not become faster after 3DP application. Comparing the start sales time of US and the Middle East, it can be found that when US acts as a resource and consumer country at the same time, namely, Scenario 2 and Scenario 3, its supply chain length is significantly shortened. If all goes well, the time spent of materials flow from oil field to distribution center will take only 15 days at the shortest. In all the scenarios the Middle East plays the role of resource and consumer country. But only in Scenario 3 does it have the ability to produce printing filaments; its start sales time is obviously ahead of schedule. This shows that the production location of 3DP filaments is an important factor in the optimization of supply chain length. When the resource country can produce filaments, the supply chain will be significantly shortened. The reduction of related opportunity cost will benefit the further promotion of 3DP in manufacturing. China is not the resource country. Even if it is able to produce filaments, the start sales time of sneakers in China is similar, no matter before or after 3DP.

5.3. Flow Volume. According to Table 10, the 3DP application will reduce about 10% of the total demand of crude oil. Moreover, in Scenario 2 and Scenario 3, crude flows more in the interior of the resource country. That has resulted in the rapid decrease in oil trade across the oceans. The specialized crude tankers and port facilities will exceed supply. Corresponding in some regions, the demand of pipeline infrastructure for oil land transportation will increase. When concerning new investment plans, the decision makers should consider the impact of 3DP on crude oil logistics.

For container transportation, in any scenario, the simplification of procedures and the self-sufficiency of the resource countries have greatly reduced the overall use of containers in the producer countries, such as China. This has led to a large surplus of container handling facilities in it. In Scenario 3, the containers in the route China-Middle East no longer carry China's sneakers to the Middle East, but the filaments from the latter to the former. Moreover, the container freight volume in this route has greatly increased compared with other scenes, for China's sales more than the Middle East's. This shows that 3DP can promote the container use in the export business of resource, which were originally exported in bulk. On the other hand, nowadays China is showing more characteristic of consumer country while this country's per capita income is growing. Its demand of import filaments will keep China's container business at a certain level.

To sum up, taking sneakers supply chain as an example, the application of 3DP will have a serious impact on the global industrial division of labor. On the whole, the demand for cross-border transport will be significantly reduced. In contrast of international crude transportation and container transportation, 3DP has a more negative impact on the former. For the latter, the cargo suitable for container can be changed from sneakers to printing filaments. The total demand of container call still maintains a certain level, but the flow direction changes. Relatively speaking, producer country suffers the greatest shock. And the container business of consumer country and resource country can get better development. When a country has the role of both resource and consumer, the material is transferred within its own territory. Because of no needs for trans-ocean transportation, the utilization of containers will be reduced.

6. 3DP Impact on the Container Hub Port

The possible impact of 3DP on the sneaker supply chain is discussed in the previous section. But the current 3DP products account for a very low proportion of global cargo flow. In the short term, it is virtually impossible to subvert the global industrial structure. The incumbent container multimodal transport system is still robust. But in the long run, more and more goods will be manufactured by 3DP. Can the case of sneakers be used for reference by other cargo categories? Will they change in the same phase? When producer country suffers the great impact of 3DP, the changing trend of its container hub port can be used to analyze the system, thus inferring the complete process of its evolution, for hub port is the core node of the whole system.

6.1. Object of Study. This section chooses one typical container hub port of the Pearl River Delta area as the object of study. The Pearl River Delta is one of China's major industry clusters. That has led to its huge international cargo throughput. China currently has 7 container ports in the world's largest 10, of which 3 are located in the Pearl River Delta region. In this part Guangzhou port is chosen, for it is the central city of this area. The famous China Import and Export Fair have been held twice per year in Guangzhou since 1957. The characteristics of the main cargo throughput in Guangzhou port can represent the situation of China's foreign trade commodities to some extent. This research first collects the classification statistics of Guangzhou port's import and export goods in recent years, and then discusses which goods are suitable for 3DP mass production in the short or middle term. Finally the container business trend of Guangzhou port after 3DP is predicted.

In order to quantify and compare the characteristics of the various goods in container transport and 3DP, it is necessary to grade their fitness of container transport and probability of 3DP mass production. For the fitness of container transport, the highest type scores 3, the moderate one scores 2, and the lowest one scores 1, respectively. For the probability of 3DP mass production, it is the same where the highest type scores 3, the moderate one scores 2, and the lowest one scores 1, respectively. The cargo throughput and the container transport fitness data are from the statistics of Guangzhou customs (2016). The probability prediction of 3DP mass production is from the Wohlers Report (2015, 2016, and 2017) and Laplume et al. (2016). According to Laplume et al. (2016), raw materials and semichemical products, such as crude, ore, and resins, were generated by other industrial processes. It is impossible for 3DP to produce them. Therefore, the probability of 3DP mass production of these goods scores 1 [12, 21–23].

The total score for the type i is Xi. Its fitness of container transport is Fi. And its probability of 3DP mass production is Pi.

$$Xi = Fi * Pi. \quad (1)$$

After calculation, Tables 12 and 13 are established, sorted by freight volume from height to low. The former is of the export goods, and the latter is of the import goods.

The higher the total score, the higher the containerization level of the goods, and the greater the possibility of 3DP mass production. For the goods of the same score, when they are manufactured by 3DP on a large scale, their relevant container business is more vulnerable. In other words, they are in the similar phase of 3DP development. The evolution of their container traffic should be similar too. Then group the goods of the same score into a class to calculate their proportion of the total throughput. For the cargoes which

Table 12: Containerization and 3DP score of major export goods of Guangzhou port.

Number	Category of goods	Freight volume (tons)	Ratio of international goods throughput	Fitness of container transport (Fi)	Probability of 3DP mass production (Pi)	Total score (Xi)
(1)	Electrical and electronic product	46730527.370	36.962%	3	2	6
(2)	Wearing apparel	2042835.393	1.616%	3	3	9
(3)	Metal semiproduct	1537353.479	1.216%	2	2	4
(4)	Construction material	1504129.317	1.190%	3	3	9
(5)	Oil and gas	1360166.590	1.076%	1	1	1
(6)	Textiles (ex apparel)	1266743.068	1.002%	3	3	9
(7)	Instrumentation	933520.837	0.738%	3	2	6
(8)	Metal product	742846.651	0.588%	3	3	9
(9)	Mechanical equipment	660896.916	0.523%	2	2	4
(10)	Other mechanical and electrical products	512008.203	0.405%	3	2	6
(11)	Luggage, suitcase, and sports goods	377554.366	0.299%	3	3	9
(12)	Agricultural and food	369267.472	0.292%	2	2	4
(13)	Conveyance	341050.774	0.270%	2	2	4
(14)	Other plastic products	339899.784	0.269%	3	3	9
(15)	Toy	313910.193	0.248%	3	3	9
(16)	Footwear	162196.734	0.128%	3	3	9
(17)	Cleaning product	148585.990	0.118%	3	2	6
(18)	Plastic semiproduct	113924.027	0.090%	3	1	3
(19)	Medicine and cosmetic	49990.431	0.040%	3	2	6
(20)	Nonmetallic mineral	43832.317	0.035%	1	1	1
(21)	Paper product	23207.723	0.018%	3	3	9
(22)	Chemical product	13691.439	0.011%	2	1	2
(23)	Wooden product	10797.701	0.009%	3	3	9
(24)	Fertilizer	5251.158	0.004%	2	1	2
(25)	Metallic mineral	2981.549	0.002%	1	1	1
(26)	Jewelry and accessory	918.885	0.001%	3	3	9

are unsuitable for 3DP, that is, their probability of 3DP mass production scores 1, they are all into a class. The goods in this class will maintain the traditional logistics mode after the large scale application of 3DP. According to the above division, Tables 14 and 15 are established. The former is of the export goods, and the latter is of the import goods.

6.2. 3DP Impact Analysis

6.2.1. Impact on Cargo of Different Classes. Sneaker belongs to the category of foot wear, which scores 9 and in class 1. The cargo of class 1 accounts for only about 7% of the total freight throughput, of which 5.368% is export and 1.963% is import. This means that even if 3DP is to a certain degree of large scale application, in the short term there will not be too much cargo similar to the evolution trend of sneaker supply chain. The prediction of 3DP causing manufacturing flow back to Europe and US will not come true for quite a long time. The existing container multimodal transport system will still operate in accordance with established patterns.

But a detailed analysis of the import and export data of Guangzhou port shows that the transportation of electrical and electronic products is very large. Its total ratio is about 55%, including 36.962% of exports and 18.243% of imports. This shows that, in the electrical era, the largest contribution to the international container system is not the basic life necessaries, such as clothes and foods, but the electronic products which could bring convenience and enjoyment to people. On the export side, China is already the world’s largest exporter of electronic products. On the import side, thanks to China’s economic development and the policy to stimulate transnational E-commerce, local consumers’ demands for foreign electronic products continue to rise. A large proportion of these products enter Mainland China through the Guangzhou port, where main components are plastic housing, metal parts, and printed circuit boards (PCB). Some of them are also equipped with liquid crystal elements. In accordance with the current technological development, excluding the plastic parts, the remaining components are difficult to be manufactured by 3DP. Another factor which

Table 13: Containerization and 3DP score of major import goods of Guangzhou port.

Number	Category of goods	Freight volume (tons)	Ratio of international goods throughput	Fitness of container transport (Fi)	Probability of 3DP mass production (Pi)	Total score (Xi)
(1)	Electrical and electronic product	23064364.250	18.243%	3	2	6
(2)	Coal	15235465.660	12.051%	1	1	1
(3)	Agricultural and food	7356585.459	5.819%	2	2	4
(4)	Metallic mineral	5002291.483	3.957%	1	1	1
(5)	Plastic semiproduct	2555210.770	2.021%	3	1	3
(6)	Metal semiproduct	2045193.182	1.618%	2	2	4
(7)	Oil and gas	1188932.120	0.940%	1	1	1
(8)	Wooden product	1105243.984	0.874%	3	3	9
(9)	Paper product	856372.732	0.677%	3	3	9
(10)	Textiles (ex apparel)	423746.435	0.335%	3	3	9
(11)	Chemical product	274391.155	0.217%	2	1	2
(12)	Pulp	252793.144	0.200%	2	1	2
(13)	Mechanical equipment	184964.670	0.146%	2	2	4
(14)	Instrumentation	169461.872	0.134%	3	2	6
(15)	Conveyance	146262.425	0.116%	2	2	4
(16)	Metal product	80137.177	0.063%	3	3	9
(17)	Dye and paint	38095.114	0.030%	3	1	3
(18)	Fiber material	27194.573	0.022%	2	1	2
(19)	Other mechanical and electrical products	21035.204	0.017%	3	2	6
(20)	Other plastic products	17502.981	0.014%	3	3	9
(21)	Medicine and cosmetic	10884.571	0.009%	3	2	6
(22)	Fertilizer	884.310	0.001%	2	1	2

cannot be ignored is that, after the parts are printed out, there is a certain process to assemble them together. It is troublesome for consumers to complete the assembly manually. So it seems unlikely that the 3DP of electrical appliances will be popular in the short term.

But today several teams are working to overcome the problem involved. For example, some laboratories have made preliminary achievements in the 3DP of PCB through the development of conductive materials (3ders.org) [24, 25]. There are teams also working hard in cheap printing of metal parts (3Dprint.com) [26] (All3dp.com) [27]. Making a product composed of a variety of materials is difficult to accomplish with just one printer, while one short board of the existing 3DP is that the same type of printer is only limited to specific materials. But now Stratasys and other companies have designed multihead-printer to print several different materials at the same workflow. As for assembly problems, this can be solved by the characteristics of 3DP. This additive manufacturing technology can generate complex geometry structure. Through effective industrial design, some structures can be printed directly without the need for embedding or riveting, which will reduce considerably assembly activities. In other words, although not as quick as the goods of class 1, the electronic products will achieve 3DP mass production in the medium term, maybe 10 to 15 years. It belongs to class 2. The proportion of the class 2 cargo is about 57%, including 38.263% of exports and 18.403% of imports. If the goods of this class can be mass-produced by 3DP, the story of the sneaker supply chain will take place. Its impact on the circulation mode of goods in Guangzhou port is quite large. The relevant parties of the container logistics system should pay close attention to this and make appropriate countermeasures in advance.

The goods of class 3 mainly include agricultural products, metal semiproducts, mechanical equipment, and conveyance. Because of the biological properties and seasonal requirements, agricultural products are not so suitable for 3DP, except for a few foods which require more in appearance than taste. As for other industrial products, due to the size, assembly procedure, and other reasons, they are difficult to produce in small distributed printers. So their manufacture is still centralized. In the maintenance of this kind of goods, there is a certain demand for 3DP spare parts. But their total amount is not large. Therefore, the change of the goods in this class has little effect on the existing container transport system.

The goods of class 4 are the raw materials and semiproducts which 3DP is unable to print. Their imports are much higher than that of exports. This conforms to the characteristics of cargo composition in the producer country. When 3DP is widely used in the manufacture of the goods of class 2, the export manufacturing activities of China will gradually move to consumer countries. At this time, China has not so much

Table 14: Containerization and 3DP classification of major export goods of Guangzhou port.

Number	Category of goods	Ratio of international goods throughput	Total score	Class	Ratio of throughput in this level
(2)	Wearing apparel	1.616%	9	1	5.368%
(4)	Construction material	1.190%	9		
(6)	Textiles (ex apparel)	1.002%	9		
(8)	Metal product	0.588%	9		
(11)	Luggage, suitcase, and sports goods	0.299%	9		
(14)	Other plastic products	0.269%	9		
(15)	Toy	0.248%	9		
(16)	Footwear	0.128%	9		
(21)	Paper product	0.018%	9		
(23)	Wooden product	0.009%	9		
(26)	Jewelry and accessory	0.001%	9		
(1)	Electrical and electronic product	36.962%	6	2	38.263%
(7)	Instrumentation	0.738%	6		
(10)	Other mechanical and electrical products	0.405%	6		
(17)	Cleaning product	0.118%	6		
(19)	Medicine and cosmetic	0.040%	6		
(3)	Metal semiproduct	1.216%	4	3	2.301%
(9)	Mechanical equipment	0.523%	4		
(12)	Agricultural and food	0.292%	4		
(13)	Conveyance	0.270%	4		
(18)	Plastic semiproduct	0.090%	3	4	1.218%
(22)	Chemical product	0.011%	2		
(24)	Fertilizer	0.004%	2		
(5)	Oil and gas	1.076%	1		
(20)	Nonmetallic mineral	0.035%	1		
(25)	Metallic mineral	0.002%	1		

needs of raw materials to manufacturing international commodities. The import of class 4 goods is mainly for the Chinese local consumers. That is to say, the amount of its import depends on the local consumption capacity. In any case, the change of such goods has very little impact on the container transport system.

6.2.2. Impact on Relevant Routes. The traditional international container liner routes generally included three major parts, Far East-US Western Coast, Europe/Mediterranean-US Eastern Coast, and Far East-Europe/Mediterranean. In recent years, with the deepening of the Panama Canal and the development of the Southern countries, new routes, such as Far East-US Eastern Coast and Far East-South America, have also opened up. Guangzhou port is an important node in the Far East. As of September 2017, the world's top 20 liner companies were operating at this port. It had 163 container routes, covering Europe, Americas, Africa, Asia, and other major ports in the worldwide range. COSCO, China Shipping, and other Chinese companies treated Guangzhou port as the base and opened the coastal routes from it to other domestic ports. Guangzhou has become the largest distribution center and conversion hub in the Southern China. Therefore, the phased impact of 3DP on this port will inevitably be transmitted through these routes and then affect the whole world.

According to Tables 14 and 15, the port's exports and imports were approximately the same. But analyzing in depth, their ratios were not the same at different class. So the 3DP impacts on them would be different. Take the cargo class as the horizontal axis and the ratio of the import and export as the vertical axis to determine Figure 5. As shown in Figure 5, whether it is Class 1 or Class 2, exports are significantly more than imports. According to the analysis of the Section 6.1, the goods of Class 1 are firstly affected by 3DP, then Class 2, and then Class 3, while Class 4 is less affected. This means that from the Class 1 phase to the Class 2 phase, the evolution like the sneaker supply chain will occur in more export goods. With the gradual development of 3DP and the outflow of manufacturing activities, the structure of import and export will be reversed while the total throughput is shrinking. Most of the declined volume comes from exports, not imports. Container operators will configure the capacity of the relevant routes based on this trend. As for the shrinking import volume, they are usually transported by bulk carriers and tankers. The impact on containers is relatively low.

Table 15: Containerization and 3DP classification of major import goods of Guangzhou port.

Number	Category of goods	Ratio of international goods throughput	Total score	Class	Ratio of throughput in this level
(8)	Wooden product	0.874%	9	1	1.963%
(9)	Paper product	0.677%	9		
(10)	Textiles (ex apparel)	0.335%	9		
(16)	Metal product	0.063%	9		
(20)	Other plastic products	0.014%	9		
(1)	Electrical and electronic product	18.243%	6	2	18.403%
(14)	Instrumentation	0.134%	6		
(19)	Other mechanical and electrical products	0.017%	6		
(21)	Medicine and cosmetic	0.009%	6		
(3)	Agricultural and food	5.819%	4	3	7.699%
(6)	Metal semi product	1.618%	4		
(13)	Mechanical equipment	0.146%	4		
(15)	Conveyance	0.116%	4		
(5)	Plastic semiproduct	2.021%	3	4	19.439%
(17)	Dye and paint	0.030%	3		
(11)	Chemical product	0.217%	2		
(12)	Pulp	0.200%	2		
(18)	Fiber material	0.022%	2		
(22)	Fertilizer	0.001%	2		
(2)	Coal	12.051%	1		
(4)	Metallic mineral	3.957%	1		
(7)	Oil and gas	0.940%	1		

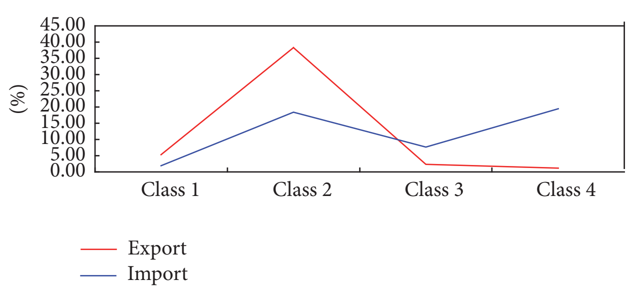

Figure 5: Export and import ratios in different classes of Guangzhou port.

Analyzing the export and import countries of Guangzhou port, maybe 3DP will not necessarily affect the container throughput as per the expected progress, for not all international container business acts as "resource country-producer country-consumer country" mode. This research is based on the sneaker supply chain among China, US, and the Middle East. But according to Wohlers Report 2017, an estimated 28.8% of all industrial 3DP systems installed worldwide were in the Asia/Pacific region. Meanwhile, 27.9% were in Europe and 38.7% were in North America. The remaining 4.5% were in Latin America, the Middle East, and Africa. At present, the relevant technologies were the most in-depth study in Europe and US, while they have been advocating the reflow of manufacturing based on 3DP. Although Japan, Korea, and China were also putting more resources into 3DP, the overall progress was not as good as the former [23]. Therefore, the most likely subversion may be the trade between China-US and China-Europe. What about other countries and regions?

Tables 16 and 17 were obtained based on Guangzhou customs statistics 2016. As shown in the two tables, European and North America were the main destination for Guangzhou port exports. Even excluding the reexports from Hong Kong SAR, their total share was still about 30%, with 14.89% for Europe and 15.62% for North America. That means the application of 3DP will significantly affect their exports in the short and medium term. But at this phase, the 3DP technologies of China do not exceed the ones of Europe and US. The cargo whose origin is Europe or US cannot be printed well in China yet. The import requirement will still exist and relevant container business will maintain a certain level.

When 3DP technology spread from Europe and US to the Far East or the latter may exceed the former through the advantage of backwardness, the global centralized mode will be completely broken. More than 70% of the cargo throughput will act just like the evolution of sneaker supply chain, no matter export or import. For imports, the largest importers of Guangzhou were Japan and Korea. Different from the primary material of resource country, Japan and

Table 16: 20 countries and regions with the largest import and export volume in Guangzhou port.

Rank	Countries and regions with the largest exports	Export trade volume (10^4 dollars)	Proportion of total export trade	Countries and regions with the largest imports	Import trade volume (10^4 dollars)	Proportion of total import trade
1	Hong Kong SAR	1,457,077.42	18.536%	Japan	930,794.97	18.215%
2	US	1,144,102.53	14.555%	Korea	623,476.88	12.201%
3	Japan	345,825.75	4.399%	US	552,985.77	10.822%
4	India	224,677.03	2.858%	South Africa	275,112.91	5.384%
5	Malaysia	221,200.65	2.814%	Taiwan, China	263,365.78	5.154%
6	UK	202,302.46	2.574%	Germany	241,677.77	4.730%
7	Mexico	191,302.65	2.434%	India	147,073.76	2.878%
8	Germany	186,400.08	2.371%	Malaysia	127,035.48	2.486%
9	Vietnam	182,761.88	2.325%	Thailand	124,773.63	2.442%
10	Korea	152,973.66	1.946%	Indonesia	112,457.75	2.201%
11	UAE	141,567.17	1.801%	Australia	101,841.09	1.993%
12	Singapore	137,449.04	1.749%	France	100,433.60	1.965%
13	Nigeria	135,350.01	1.722%	Vietnam	96,774.91	1.894%
14	Thailand	132,306.75	1.683%	Netherlands	89,939.46	1.760%
15	Indonesia	130,854.57	1.665%	UAE	86,787.34	1.698%
16	Taiwan, China	126,597.45	1.611%	Italy	82,809.35	1.621%
17	Saudi Arabia	125,249.90	1.593%	Singapore	75,027.86	1.468%
18	Philippines	122,706.52	1.561%	Brazil	62,952.66	1.232%
19	Netherlands	118,423.16	1.507%	Philippines	54,007.56	1.057%
20	Australia	117,262.73	1.492%	Hong Kong SAR	52,748.18	1.032%

Table 17: Continents with the largest import and export volume in Guangzhou port.

Rank	Continents with the largest exports	Export trade volume (10^4 dollars)	Proportion of total export trade	Continents with the largest imports	Import trade volume (10^4 dollars)	Proportion of total import trade
1	Asia-Pacific	3,269,799.47	41.60%	Asia-Pacific	2620400.69	51.28%
2	North America	1,228,080.74	15.62%	Europe	808,570.14	15.82%
3	Europe	1,170,198.67	14.89%	North America	595,338.74	11.65%
4	Africa	844,983.87	10.75%	Africa	315,775.44	6.18%
5	Middle East	498,906.26	6.35%	Middle Asia	286,013.87	5.60%
6	Latin America	440,747.19	5.61%	South Asia	183,097.50	3.58%
7	South Asia	367,005.38	4.67%	Middle East	150,693.53	2.95%
8	Middle Asia	40,979.59	0.52%	Latin America	149,325.81	2.92%

Korea tended to sell their high-tech components to China, such as the camera and LCD panel for mobile phone and appliances. Chinese foundries assembled these and other parts into finished product and then exported. If 3DP leads to distributed production, these countries can send these components directly to Europe and US and print the final product at the local distribution center. But on the other hand, in recent years, China's technological advances have achieved some components being produced locally. Japan, Korea, and China all belong to the Far East. If such products still cannot be printed well in the consumer countries, the whole Far East will maintain their exports.

But even in the whole Asia, only China, India, Japan, Korea, and Singapore have achieved remarkable results in the research and development of 3DP (Wohlers Reports 2017) [23]. Other regions, including ASEAN, Central Asia, and most of the Middle East, were still not paying enough attention to it. Coupled with the trade volume with Latin America and Africa, the container business between Guangzhou port and developing countries should not be affected by 3DP for a long time. It will be still dominated by traditional mode.

Different from 3DP which leads to distributed production, the "Belt and Road" initiative launched by China is regarded as another important factor that may impact the existing international industrial division, but with the opposite direction. The initiative included a series of measures to boost international trade and globalization, such as funding support, industrial transfer, and infrastructure construction.

It has been welcomed by regions such as ASEAN, Central Asia, and Africa. Guangzhou port was an important hub among China and these countries to strengthen ties with each other. When they improve their container infrastructure, Guangzhou port container business with them may be further improved (Wang et al., 2017) [28]. This means that the container business reduction of developed countries will be covered by that of the above developing countries.

7. Conclusion

The application of container multimodal transport system can standardize the process of international logistics, reduce the time and risk of trans-continental transportation, and significantly cut down the cost of global commodity flow. Its prosperity is an important promoter of postwar globalization. But as consumer tastes improve, their choice of commodities not only is based on price factors, but also emphasizes personalization and quick acquisition. In the meantime, the severe global economic situation makes the trade protectionism, some governments in consumer countries introduced a number of measures to encourage manufacturing backflow, and some of the commodity production was gradually transferring to the end of supply chain. Global manufacturing activities are changing from centralized to distributed one. This has promoted the rapid development of 3DP and other digital manufacturing technology in recent years. Will the incumbent globalization process be interrupted? Will the existing industrial pattern collapse? Will this have a serious impact on the container logistics system? This is the starting point of this research.

7.1. 3DP Impact on Transnational Container Logistics Business. In the first step of the derivation, this research begins with a case study of 3DP sneakers. The model of transnational supply chain is established using system dynamics, and the different characteristics of the material flow under three possible evolution scenarios are investigated. Simulation results show that the application of 3DP will make the global industrial division of "resource-producer-consumer" suffere a severe shock. The supply chain will change significantly in three aspects: flow direction, flow velocity, and flow volume. In either case, the aggregate demand for international transport will be significantly reduced. For different stages of the chain, the bulk transportation of crude is more negatively affected by 3DP than the container transportation of semiproducts and final products. The reason is that the shipment object of container can change from sneakers to printing filaments, and its total volume can still maintain a certain level.

However, how much cargo suitable for container will be replaced from the finished products to the printing filaments? It needs further investigation. That is because an important uncertainty is recycled printing material. After the 3DP products are abandoned, some of them can be handled properly for recycling. This may greatly reduce the demand of new filament. In the conventional process, the recycling of plastic waste was the responsibility of a professional company, which requires proper qualification and a lot of upfront investment. And the scale of garbage collection is needed to meet certain standards. But 3DP allows consumers themselves to become qualified environmentalists. Initially, large 3DP enterprises were not willing to develop the recycled business, for the quality requirement and profit pursuit of industrial level filaments. The recycled materials were developed more by some start-up companies (Treehugger.com) [29]. However, with the deterioration of the earth's environment, the young consumers, who were called the Generation Y and the main supporters of 3DP products, had changed their consumption concept greatly (Gurtner & Soyez, 2016) [30]. They would choose more environmental-friendly products (Kreiger et al. 2014) [31]. This would also promote professional companies to develop related recycling processes at industrial level. For example, 3D Systems Company has designed a 3D printer called EKOCYCLE Cube which uses recycled plastic filaments (3Dsystems.com) [32]. The extent of distributed production will be further enhanced if more large enterprises participate in this business. By then, end-consumers may tend to use local recycled filaments instead of newly made ones from overseas. That will once again reduce the international container demand. As a result, consumer perception of environmental protection is an unknown variable affecting container operations in the 3DP era. The relevant data needs to be collected continuously for more accurate forecasts.

7.2. 3DP Impact on Global Container Multimodal System. Will the trend of the sneaker supply chain happen in other goods? How to infer the complete evolution process of global container logistics system through the changes of various supply chain? In the second step of the derivation, this research establishes a comprehensive index system based on the international throughput data of Guangzhou port and the modern 3DP documents. The evaluations suggest that, according to current trends of 3DP, in the short term only about 7% of the cargo throughput will change like the sneakers supply chain. This will not have a significant impact on the container system. However, when the 3DP mass production of electrical products has come true, about 60% of the cargo will undergo obvious variation. The characteristics of cargo handling in Guangzhou port are typical in China. This means that China's role as a producer of the global industry will be subverted.

3DP mass production of electrical products will be the break sign of the incumbent global industrial pattern. By then, more products will be transferred from centralized production to distributed production. However, the return of manufacturing from producer countries to consumer countries may not happen immediately. 3DP reduces the advantage of labor cost of producer countries but raises the importance of raw materials of resource countries. While several resource countries are also committed to 3DP research and development, in the premise to achieve the necessary technical ability, part of the manufacturing activities may be diverted to these regions. In this research, crude oil is used as the main resource. But in fact, resources such as minerals and agricultural products are also the main components of international raw materials. If all the countries use their own natural resource advantages to strengthen the trade of 3DP materials, even if the bulk cargo's trans-ocean transportation is reduced, the service objects of containers will be converted from finished products to 3DP materials. This allows the container multimodal transport system to continue running at a certain level, within its flow direction, velocity, and volume changing.

For different countries, 3DP has different impact. The producer country is shocked the most. Without the own demand of the local consumers, the outflow of manufacturing activities will significantly reduce its container business. At the same time, the inflow of manufacturing has led to a certain increase in volume of container traffic in consumer country. But the impact on the resource country is twofold. Its crude oil exports will decline, while its container business is likely to grow. This is because the relevant container demand will be greatly stimulated when the export goods change from crude to filaments. On the other hand, when a country has both roles of resource and consumer countries, the self-sufficient supply chain makes the production and marketing happen domestically. The demand for multimodal transportation has decreased significantly. More pure land transport will prevail. As container is more suitable for the former, the container trailer may be replaced by ordinary freight truck. This will also reduce the utilization of containers.

The above discussion has assumed that the resource countries are able to master the key 3DP technologies to achieve self-sufficiency in the finished product. But the analysis of Guangzhou port shows that the impact of 3DP is not immediate and comprehensive. It has different impacts on international goods of various class and countries. As far as crude oil is concerned, US can play the role of resource and consumer countries at the same time. So the manufacturing activities of Class 1 and Class 2 will gradually flow back to this country. But most of Europe is not resource countries. Although some European countries are leading in frontier 3DP technology, its large scale application in Europe is constrained by filament resource. Even taking into account the use of recycled materials, the container business between Europe and resource country still needs to maintain a certain level to meet the needs of local consumers. For traditional oil producing regions, the Middle East, Africa, and South America, while Dubai, UAE, is ambitious to become a regional 3DP hub, the rest of the countries seem not to know the appropriate technology well. Moreover, many resource countries belong to the type of a large population but low income. Although 3DP demand in these places may exist, its relatively high prices will make these countries for a long time not become the mainstream areas of this technology. Their industrial mode tends to be traditional. On the other hand, when the producer country is faced with the deglobalization which is the result of 3DP application and trade protectionism, it may actively respond with measures to maintain consistency of the process of globalization, such as Belt and Road initiative proposed by China. Moreover, producer country had a lot of opportunities to contact with the advanced production frontier. It could be easier to grasp relevant technologies for their own use, such as Chinese innovation policy spawning many 3DP research teams in recent years (Chen, 2015) [33]. In other words, when the mass application of 3DP realizes, the future container business for US will be reduced obviously and then Europe's. But freight traffic in other regions may remain unchanged or even rise to cover the share of the former. Technology development and trade cooperation will work together in this container system to make more and more dynamic changes.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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