

Analysis of Supply Chain Network Design Model with Quality Cost

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Abstract. Designing the supply chain network model that takes into account product quality could be one of the most key factors that significantly improve the performance of organizations and also affects the most customer satisfaction in a long-term period. However, this model is based on a single product and a single production stage. This paper aims at designing a three-echelon supply chain model including multiple suppliers, multiple manufacturers with multi-stages inspection, and multiple customers. The mathematical problem is formulated with Cost of Quality (COQ) integrated into Supply Chain Network Design (SCND) to minimize the total supply chain cost involving transportation costs and production costs. Further, the paper proposes a meta-heuristic called Particle Swarm Optimization algorithm used to solve the model for the supply chain lot size and sampling inspection strategy. From the numerical data of the case study, the developed technique can determine the minimum of total supply chain cost at quality inspection 30.95%.

Keywords: Supply Chain Network Design, Quality Cost, Cost of Quality, COQ, PSO algorithm

1. Introduction

The supply chain management strategy has been recognized as one of the most important activities in numerous organizations to improve the efficiency of operations. The higher competitive market makes the supply chain management more significant. Regularly, the organizations have operated independently. They have their own purposes and are often conflicting on how to increase the product distribution, enhance the distribution systems, improve the service level and decrease logistics costs. Therefore, a mechanism through which these issues can be integrated together is required called Supply Chain Network Design (SCND).

However, most companies aim to increase the supply chain quality at low cost. They usually concentrate supply chain operation performance improvement by looking at the supply chain process itself for maintaining the profit margins without considering the quality. In general, organization competitiveness can be affected by the costs of correcting errors, product reworking, product rejection, product reclamation, etc. More than 20% of sales revenue over a wide range of industries has forecasted to be the quality-related cost of ineffective activities [1]. As manufacturers struggle to achieve these purposes they need to confront the point of trade-offs balancing between quality increment and costs reduction. It can be seen that SCND issues have been very considerably mentioned only in the field of operation costs. The concept of Cost of Quality (COQ) integrated into the network design rarely finds in researches. It would be better advantageous for the organization if they can derive a cost indicator for quality along with the costs of operation which could reflect the better performance of the system.

In this paper, we consider SCND model that computes the COQ of a single product for a whole supply chain based on decision factors of lot size and demand and others decisions within the manufacturing plant, such as the defective fractions, and the proportion of quality inspection. The purpose of this study is to decrease the number of defects that cause the failure cost and to increase the reliability of the organization. In addition, the technique of modelling can lead to an NP-hard problem. Thus, the optimal solution is difficult to be generalized under the general form but the optimum lot size and inspection ratio calculation can be

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solved by Particle Swarm Optimization (PSO) algorithm. This paper provides the advantaged strategy to improve the performance of the supply chain which can meet customer needs together with reducing the environmental impact. It will lead to cost-effective use of resources and reduce wastes in the production process that can be the opportunity to gain a higher profit to the organization.

The remaining parts of the paper are organized as follows. Section 2 presents a literature review of the related topics. Section 3 is the problem description and assumptions. In Section 4, the mathematical modelling is presented. Section 5 evaluates the model and the solution algorithms. Section 6 concludes the paper and provides some future research directions. Finally, Section 7 is an acknowledgement.

2. Literature Review

From the reviews of past researches, many organizations have explored better approaches for designing and managing their supply chain system for achieving economical cost and maintaining a higher profit. Furthermore, the quality can help to prevent wastes generated from upstream to the downstream supply chain attaining more satisfying for customers. Thereby, one of the paths that can lead to efficiency improvement is designing the optimal lot size and inspection strategies in the supply chain system. There are several solution approaches which could be summarized as follows:

2.1. Supply chain network design (SCND) integrated COQ

Altiparmak et al. [2] proposed a steady-state genetic algorithm (ssGA) for the single-source, multi-product, and multi-stage Supply Chain Network Design problem by comparing its results with those obtained from CPLEX, Lagrangean heuristic, hybrid genetic algorithm and simulated annealing on a set of different sizes of supply chain network. The experimental study showed that the ssGA found better heuristic solutions than the other approaches. Pan and Nagi [3] formulated the mathematical model for multi-echelon Supply Chain Network Design in agile manufacturing to minimize the total operational costs composed of fixed alliance costs between two companies, production, holding costs, and transportation costs under production and transportation capacity limits.

In addition, there are studies toward the integration of applying quality into a supply chain network. Das [4] proposed a multi-stage global SC mathematical model in order to prevent recall risks by integrating 2 systems, a) a quality-based supply management system to connect prospective suppliers and b) integrating a critical-to-quality approval process for manufacturing facilities. Ramudhin et al. [5] also focused on integrating COQ in SC. The study presented a mathematical formulation that integrates COQ into the modelling of an SC network for a single-product, three-echelon system and seeks to minimize the overall operational and quality costs. Then, Alzaman et al. [6] presented a Supply Chain Network Design with a cost of quality integration in a case study of the aerospace industry solving by simulated annealing (SA)-based solution procedure to make decisions based on operational costs and quality related to non-conformance costs. Castillo-Villar et al. [7] proposed supply-chain network modelling considering the Cost of Quality along with the conventional production and distribution costs with two solution methods based on a simulated annealing (SA) and a genetic algorithm (GA) were performed for computational experiments on test instances.

2.2. Lot sizing related logistics design

Barzoki et al. [8] developed a simulation model based on GTOQ model from Boucher's model. The new model calls Group Technology Order Quantity Rework (GTOQR) aiming to find the optimum lot sizing to maximize profit for different types of work-in-process inventory consisting of a) unfinished products, b) good-quality products, c) non-rework products, and d) good-quality products in inventory. Moreover, in the research of Bouslah et al. [9], they conducted a similar study and presented the level of inventory during the dynamic production process to find an economical lot size and the appropriate time span in each production process in order to maximize production efficiency and consistently align with whole processes. Lately, Ullah and Kang [10] developed a model called Group Technology Order Quantity (GTOQIRR). This model added 3 more factors into consideration which are a) cost of inspection, b) cost of rework, and c) cost of rejection. The model assumed that the condition is a single-stage imperfect production system. This study

also aimed to find the economical lot size focusing on Work-in-process. The result is shown that the lot sizing relied mostly on the minimum average cost.

From the review of relevant literature, although there are many types of research about the SCND, there are no studies considering on COQ with the optimal lot size and sampling inspection strategy excepted the studies of [5], [7] and [10] which has some concepts close to the researcher's interest. Moreover, none of the above-mentioned research works considers the solution using the Particle Swarm Optimization (PSO) algorithm in Supply Chain Network Design. Therefore, this paper presented the alternative model that integrates COQ for supply chain network planning for the imperfection production process to achieve the lowest cost of the whole supply chain system using the Swarm-based Intelligence technique, PSO algorithm.

3. Problem Description

3.1. Problem statement

In this section, the problem statement and assumptions required to model the problem are introduced following with the mathematical formulation. The structure of the considered supply chain network is indicated in Fig. 1.

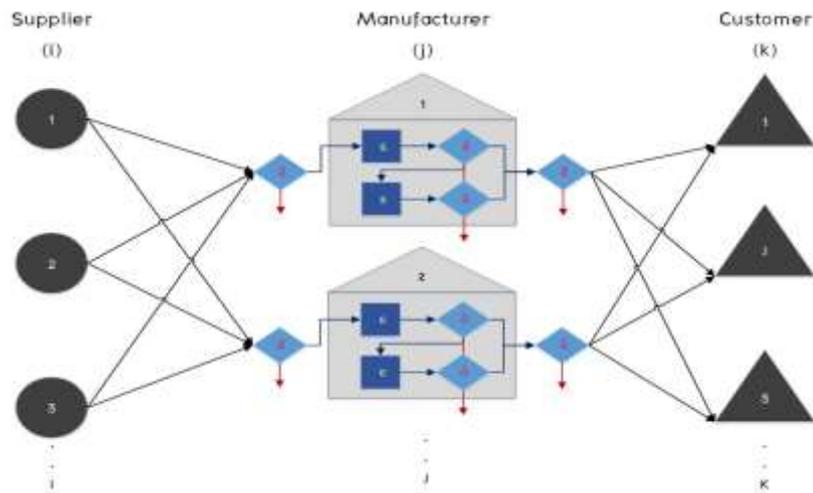


Fig. 1: Three-echelon supply chain diagram under quality inspection system.

We consider the three-echelon supply chain model under quality inspection system which is mainly extended the concept idea from [10]. The modelling has been designed for evaluating the transportation cost and also production cost including quality concern from upstream to the downstream supply chain; suppliers to end customers. There is quality control assembled throughout the production process using the reasonable proportion of quality checks that will be applied to all inspection points in every manufacturer. The appropriate inspection ratios are an indicator of the effectiveness of quality inspection. In our model, it can be seen that the system has divided into 3 processes and has 4 phases of checkpoints represented by r . We define that supplier, manufacturer and customer are represented by i , j and k indices.

However, before focusing on the cost calculation, mass balance computing in the whole process is necessary to provide a clear understanding of the mathematical modelling of the multi-stage process. Beginning with the first phase ($r=0$), pre-production process, incoming materials are separated into 2 types after passing through the first inspection point ($\delta_{j,0}$) consist of good quality materials ($w_{1,j,1}$), poor quality materials ($w_{2,j,1}$). At this process, defects can be made a complaint about reclaiming to the original supplier by a proportion of factories policy ($f_{0,j,0}$). Then, the production process has been started. The amount of waste ($\varepsilon_{j,r}$) can be varied depending on the production interval. Those poor products will be sent to the inspection process which will be classified into 3 categories: replaceable wastes ($f_{1,j,r}$), reworkable wastes ($f_{2,j,r}$), and rejected wastes ($f_{3,j,r}$) in both phase 1 and 2 ($\delta_{j,1}, \delta_{j,2}$). The last process, the total outcomes from the manufacturer j contains the good products ($G_{pro,j}$), poor products ($P_{pro,j}$) and scraps (Scp_j). Finally, in order to avoid the high claim cost, we have to decrease the amount of poor quality products by establishing the final inspection point ($\delta_{j,3}$) before conveying to customers.

3.2. Assumptions

- A single product is modeled.
- Demand rate is constant, deterministic and continuous
- No stoppage is allowed during the manufacturing.
- Every manufacturer has the same fixed parameters.
- Costs are calculated depending on a single lot size per year
- All inspection proportion are equal in every phase.
- The quality inspection process must be 100% accurate; there is no mistake in the inspection process, i.e. no rejection of good quality products and not accepting poor quality products.
- There is penalty cost due to the poor products that reaches to customers.

4. Modeling

4.1. Associated cost analysis

The modelling essentially begins with the calculation of transportation cost and production cost associated with the product's quality and the optimal lot size calculation. The system has separated into the stage of pre-production, production and post-production process. Before starting all costs calculation, we have to compute the processing time, average operation time and cycle time in regard to the total demand and lot size. In addition, the manufacturing time, rework time and inspection time are used to calculate the total processing time. Then, costs in term of production are calculated composed of pre-production cost, production cost, energy cost, inventory holding cost, work-in-process holding cost, treatment cost and penalty cost as follows (1);

$$TPC_j = C_j^{pre} + C_j^{production} + C_j^{energy} + C_j^{IH} + C_j^{WIP} + C_j^{post} + C_j^{treat} + C_j^{penalty} \quad (1)$$

From the above-mentioned costs, the production cost consists of material cost, setup cost, processing cost and quality cost. Thus, the total cost of manufacturing can be expanded that

$$TPC_j = \left(\frac{t_{insp0_j} Insp0_j (\delta_{j,0} Q_{in_j})}{t_c \times 60} + \left(\frac{Cl_{ij} Q_{cl_{ij}}}{t_c} \right) \right) + \left(\frac{k_j t_{s_j} + \sum Mat_{ij} Q_{ij} + Q_{in_j} t_{m_j} k_j + (t_{insp_j} Insp_j (\delta_{j,1} Q_{in_j} + \delta_{j,2} R_{w_j,1}) + k_j t_{r_{w_j}} R_{w_j,1})}{t_c \times 60} \right) \\ + \left(\frac{En_j}{t_c} \right) \left[\begin{array}{l} P_{mc_j} \left(t_{s_j} + \frac{t_{m_j} Q_{in_j} + t_{r_{w_j}} R_{w_j,1}}{60} \right) \\ + P_{insp_j} \left(\frac{t_{insp1_j} (Q_{in_j} \delta_{j,1}) + t_{insp1_j} (R_{w_j,1} \delta_{j,2})}{60} \right) \end{array} \right] + \left(\frac{1}{2t_c} \right) (a_j) \left(\frac{G_{pro_j}}{+P_{pro_j}} \right) \left[\frac{t_{s_j} + t_{m_j} Q_{in_j} + t_{insp_j} (Q_{in_j} \delta_{j,1}) + t_{r_{w_j}} R_{w_j,1} + t_{insp_j} (R_{w_j,1} \delta_{j,2})}{Q_{in_j}} \right] \\ + \left(\frac{1}{2t_c} \right) (Q_{in_j} \overline{Mat_i} + scrap_j c_j) a_j + \left(\frac{t_{insp1_j} Insp1_j (\delta_{j,3} Q_{out_j})}{t_c \times 60} \right) + \left(\frac{(treat_j)(scrap_j)}{t_c} \right) + \left(\frac{(P_{pro_j})(Pn_j)}{t_c} \right) \quad (2)$$

4.2. Mathematical model

To consider the supply chain cost, the focus of this research is on the traditional costing calculation which is the minimization of the total cost supply chain network depending on the supply chain lot size and sampling inspection as the decision variables. Additionally, the objective function is the combination of the production integrated quality cost and the transportation cost to satisfy the demand of customers with the lowest cost as described below:

Decision Variables:

- X_{ij} Lot size of raw materials sent from supplier i to manufacturer j (unit/year)
 Y_{jk} Lot size of raw materials sent from manufacturer j to customer k (unit/year)
 $\delta_{j,r}$ Inspection proportion of manufacturer j phase r

Objective function:

$$Min z = \sum_{i \in I} \sum_{j \in J} TrC_{ij} X_{ij} + \sum_{j \in J} TPC_j + \sum_{j \in J} \sum_{k \in K} TrC_{jk} Y_{jk} \quad (3)$$

Subject to:

$$\sum_{j \in J} X_{ij} \leq S_i \quad \forall i \quad (4)$$

$$\sum_{j \in J} Y_{jk} \geq D_k \quad \forall k \quad (5)$$

$$\sum_{i \in I} X_{ij} \geq Cap_j \quad \forall j \quad (6)$$

$$\sum_{k \in K} Y_{jk} \leq Gpro_j + Ppro_j \quad \forall j \quad (7)$$

$$Gpro_j + Ppro_j \leq Cap_j \quad \forall j \quad (8)$$

$$0 \leq \delta_{j,r} \leq 1 \quad \forall j \forall r \quad (9)$$

$$X_{ij}, Y_{jk} \geq 0 \quad \forall i \forall j \forall k \quad (10)$$

The objective function given in (3) is to minimize the total cost of the supply chain which contains 3 components. The first term is the transportation cost of raw materials from suppliers to manufacturers. The second term represents the transportation cost of finished products from manufacturers to customers. Lastly, the third component determines the production cost involved the cost of quality.

The constraint in the model starts with constraint (4), which ensures that supply at suppliers is not exceeded. Constraint (5) enforces that all manufacturers are producing enough products to meet customers' demand. Constraint (6) ensures that the number of incoming materials does not exceed the production capacity. Constraint (7) and (8) specify that the sum of good and poor quality products of the manufacturer's production should be produced enough in order to be sufficient for the number of products delivered to customers and does not exceed its capacity given. Constraint (9) and (10) define the status of the decision variables.

4.3. Solution methodology using PSO algorithm

Establishing a systematized model with centralized planning of the supply chain physically is a large scale and complicated problem. This kind of mathematical models is hard to solve optimally in most realistic cases [11]. Thus, to accomplish near-optimal solutions in term of large size instances of the proposed model, the alternative solution techniques are needed to be applicable.

PSO algorithm is one of the population-based evolutionary algorithms techniques which introduced by [12] in 1995. The inspiration of this idea comes from the social behaviour of a flock of birds and fishes. In this algorithm, the potential solutions are birds that search for food, called particles. Each particle with use of specified rules searches space with a velocity to find a new position [13]. PSO begins with initial population of solutions that can be generated randomly or received from the final population of other algorithms. Then, PSO searches for better solutions by updating generations. Achieving new positions (solutions) are related to three terms:

Inertia term: each particle desires to continue its former direction with weight w .

Cognitive term: each particle wants to move toward the best position that it experiences (X_{lb}^i) with coefficient C_1 .

Social learning term: each particle tries to move toward the best position that the swarm experience (X_{gb}) with coefficient C_2 .

When find the X_{lb}^i value and X_{gb} value, every particle will update its velocity and position as follows (Eq. (11) and (12)):

$$V_{k+1}^i = w \times V_k^i + C_1 \times r_1 (X_{lb}^i - X_k^i) + C_2 \times r_2 (X_{gb} - X_k^i). \quad (11)$$

$$X_{k+1}^i = V_{k+1}^i + X_k^i \quad (12)$$

where v_k^i is velocity of particle i at time k , w is the weight inertia, C_1 and C_2 are acceleration coefficients, x_k^i is position of particle i at time k , x_{lb}^i is personal best and x_{gb} is global best, r_1 and r_2 are random numbers uniformly distributed within the range $[0,1]$ [14].

In our model, there are 5 controls to be determined parameters used: the number of particles, which is the population size, the number of iteration, lower-upper bound of inertia weight and the acceleration factor. These parameters are shown in Table 1.

Table 1: PSO parameters used in this study

Parameter	Value
Number of particle	40
Number of iteration	500
Maximum Inertia Weight (w_{max})	0.9
Minimum Inertia Weight (w_{min})	0.4
Acceleration Constant ($C1=C2$)	2

5. Experimental Results

In this paper, the applicability of the model's ability to integrate COQ into SCND as a way of ensuring product quality in order to prevent much more defects resulted in the higher penalty cost. The considered problem is NP-hard and difficult to solve using the exact method. Then, the PSO algorithm has been implemented to find the possible optimal solution using MATLAB. The model is illustrated by 3 echelon supply chain network including 3 suppliers, 2 manufacturers and 3 customers using some acquired data from the manufacturer in a case study together with some experimental parameters. Some data such as material costs and transportation costs are kept confidential.

However, to simplify the model, we remark that all manufacturers have the same parameters as defined in the assumption of the problem. The present production has no replacement and reworks process in phase 2. The model supposes that inspection ratio in all phases have the same value. Assuming that the three suppliers have capacity of 7500, 8000 and 7100 materials per year and customers require 5500, 6000 and 5800 products per year respectively. The production capacity of manufacturer 1 and 2 are 10000 and 9000 per year. The penalty cost (Pn) = \$118 per unit, the treatment cost ($treat$) = \$2.50 per unit percentage inventory holding costs (a) = 30%, electrical rate (En) = \$0.11 per kWh, operating person each manufacturer = 12, inspection person (including 3 production stages) = 34, labour cost (LC) = \$12 per day and labour hour (h) = 8 hours per day. Moreover, the production parameters used in the mass balance calculation are shown in Table 2 for all manufacturers.

Table 2: Manufacturing data

Input Parameter	Value	Input Parameter	Value
$\varepsilon_{j,1} = \varepsilon_{j,2}$	2.5%	t_{s_j}	19.50
$f_{0,j,0}$	100%	t_{m_j}	50.59
$f_{1,j,1}$	10%	t_{insp_j}	12.64
$f_{2,j,1}$	50%	t_{insp0_j}	3.00
$f_{3,j,1}$	40%	t_{insp1_j}	7.00
$f_{1,j,2} = 0$	-	$t_{rw_j} = t_{m_j}$	50.59
$f_{2,j,2} = 0$	-	P_{mc_j}	127.20
$f_{3,j,2}$	100%	P_{insp_j}	8.10

The experimental results are presented in 4 different numeric data considering inbound and outbound lot size including the percentage of inspection as Table 3. Furthermore, the associated costs are shown in Table 4: pre-production cost, production cost, energy cost, inventory holding, work-in-process holding cost, treatment cost, penalty cost, transportation cost, cost of reclaim and total supply chain cost.

Table 3: Inspection plan and production lot size

Inspection Proportion	Lot size (unit)												Computational Time (sec)
	X11	X21	X31	X12	X22	X32	Y11	Y21	Y12	Y22	Y13	Y23	
$\delta_{j,r} = 0\%$	4,255	5,745	0	1,604	0	7,400	0	5,500	6,200	0	3,289	2,512	22.4142
$\delta_{j,r} = 15\%$	277	6,805	2,974	6,134	0	2,930	3,491	2,080	41	6,200	5,800	0	21.7428
$\delta_{j,r} = 30.95\%$	3,603	6,514	0	1,719	0	7,400	3,223	2,286	0	6,200	5,800	0	23.1355
$\delta_{j,r} = 40\%$	0	3,250	6,900	6,900	2,266	0	0	5,500	6,200	0	3,294	2,506	21.2836

Table 4: Cost analysis of supply chain network modelling

Inspection Proportion	Cost (\$)										Total Cost (\$)
	Pre	Pro	En	IH	WIP	Treat	Post	Pen	Trans	Claim	
$\delta_{j,r} = 0\%$	0	334,303.50	224,747.05	58,857.11	6,746.42	0	0	143,649.36	242,134.30	0	1,010,437.75
$\delta_{j,r} = 15\%$	2,138.16	355,403.43	226,284.93	60,467.53	6,959.89	519.73	4,989.04	94,444.01	243,392.00	145.16	994,743.91
$\delta_{j,r} = 30.95\%$	4,410.83	378,173.44	227,629.19	62,163.11	7,150.98	836.13	10,291.93	55,631.99	245,057.90	287.55	991,633.10
$\delta_{j,r} = 40\%$	5,700.42	390,550.51	228,363.61	63,133.23	7,252.89	942.60	13,300.98	39,922.77	250,014.20	368.86	999,550.10

From the above-mentioned analysis, the result shows that the optimal solution which requires 30.95% of sampling inspection can reach the minimum cost with their specific lot size. We found the external failure cost of 5.61% of the penalty cost by total cost if non-conformance products are detected by customers. Moreover, it can be noticed that whenever the organization has no taking into account the quality of products, there are not only increasing the cost but also decreasing the reliability. However, if firms need to guarantee that the percentage of error should be not over the quality control policy, it is possible to provide more constraints in the modelling.

6. Conclusions and Suggestions for Further Research

As concluded from the previous literature review on the SCND problems, most of them are considered in term of operational cost. Several research works are not confronting in the application of COQ. It can be seen that quality concern is very necessary which can be the reliability indicator. This paper introduced an approach to design a dynamic SCND in which formulated with COQ to minimize the total supply chain cost involving transportation costs and production costs. The model has investigated a three-echelon supply chain network using the same parameters for every manufacturer. The computational experiments present that whenever a manufacturer invests more budget in quality inspection, the trade-off between cost and customers' satisfaction are initiated. Therefore, an appropriate lot size and inspection proportion have an effect on the total cost regarding the customers' satisfaction and also long-term reliability.

Consequently, the model simultaneously considered the strategic and tactical planning decisions which can serve as an effective tool in designing the supply chain network for decision-makers. Nonetheless, the model has simply designed by concentrating on material and product as a single component. In addition, all sampling inspections have been limited by an equivalent proportion. A possibility for future research work, the multi-component, and multi-objective capacitated SCND problem integrated COQ could be studied. To be a more realistic circumstance, the model can be applied to the different inspection proportion. Apart from that, lot size can be separated as a partial lot size. Further, and developed additional algorithms such as the GA, ACO, and ABC for comparing the performance of the proposed model.

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