Expert Systems with Applications 39 (2012) 10160–10176

Contents lists available at SciVerse ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Application of particle swarm intelligence algorithms in supply chain network architecture optimization

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ARTICLE INFO

Keywords:
Supply chain management
Particle swarm optimization/intelligence
Integration
Optimization

ABSTRACT

In today's globalization, the success of an industry is dependent on cost effective supply chain management under various markets, logistics and production uncertainties. Uncertainties in the supply chain usually decrease profit, i.e. increase total supply chain cost. Demand uncertainty and constraints posed by the every echelon are important factors to be considered in the supply chain design operations. Optimization is no longer a luxury but has become the order of the day. This paper specifically deals with the modeling and optimization of a three echelon supply chain network using the particle swarm optimization/intelligence algorithms.

1. Introduction

In 21st century, particularly with the globalization of the world economy and revolutionary developments of information technology, the critical challenge to manufacturing enterprises is to become flexible, responsive and quickly adapt to environment changes under a dynamic and uncertain business environment. Moreover, these changes generally reflect on their supply chain. The ability to manage the complete supply chain network (SCN) and to optimize decisions is increasingly being recognized as a crucial competitive factor in order to make good decisions within a SCN. The supply chain is made up of all the activities required to deliver products to the customer, from designing product to receiving orders, procuring materials, marketing, manufacturing, logistics, customer service, receiving payment and so on. Anyone, anything, anywhere that influences a product's time-to-market, price, quality, information exchange or delivery, among other activities, is part of the supply chain. The old way of delivering product was to develop relatively inaccurate projections of demand, then manufacture the product and fill up warehouses with finished goods. The old ways are fading fast as management across all industries has come to accept that collaboration with customers and suppliers in the planning and replenishment process can and must be made to work very effectively. As customers and suppliers band together in mutually beneficial partnerships, the need of integrated supply chain management processes and systems are more evident and becomes a very high business priority. For many companies, it has become clear that a supply chain that flows information and material best can be a significant differentiator, the competitive winner. All the way to the boardroom, improving supply chain management is getting lots of attention because forward-thinking management knows it is the best strategy to increase and maintain market share, reduce costs, minimize inventories and of course, improve profits. In many industries, market share will be won and lost based on supply chain performance. With the stakes so high, there is a frenzy of activity along the supply chain front. Executive managers are assessing how their companies do business, especially in supply chain activities. They often find dysfunctional sets of policies, processes, systems and measurements. And these exist at all points in the supply chain, including business partners. The former vague image of a company of silos is very apparent and, most importantly, a new clarity of needs and goals emerges for supply chain management. There is a need to transform from dysfunctional and unsynchronized decision making – which results in disintegrated and very costly supply activities – to a supply chain that performs in such a way that it is one of the company's competitive advantages.

Effectively integrating the information and material flows within the demand and supply process is what supply chain management is all about. In most companies, however, two major and very interdependent issues must be simultaneously addressed. The first deals with delivering products with customer-acceptable quality, with very short lead times, at a customer-acceptable cost – while keeping inventories throughout the supply chain at a minimum. The second issue, which tends to be less understood and accepted, is the need for high-quality, relevant and timely information that is provided when it needs to be known. For any customers and manufacturers, business processes and support systems will not measure up to the task

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0957-4174/$ - see front matter
doi:10.1016/j.eswa.2012.02.116

of quickly providing planning and execution information from the marketplace to production and onto vendors so that the customer's objectives are consistently met. The fact is, most information supplied is excessive, often late and frequently inaccurate. Regardless of industry and customer base, more effective supply chain management will be a prerequisite to future success. In fact, effective supply chain management must become an integral part of competitive and survival strategy.

2. Background

A large amount of literature on supply management places great emphasis on integration of different components of the chain. Finding the right strategy that is optimal across the entire supply chain is a huge challenge (Quinn, 2000; Simchi-Levi, Kaminsky, & Simchi-Levi, 2001). An emerging principle for the management of supply chains is that a supply chain perspective provides the opportunity for significant savings in inventories from the better coordination and proper scheduling purchasing, production and distribution of goods across the supply chain network. As described by Hicks (1999) supply chains can be defined as "…real world systems that transform raw materials and resources into end products that are consumed by customers. Supply chains encompass a series of steps that add value through time, place, and material transformation. Each manufacturer or distributor has some subset of the supply chain that it must manage and run profitably and efficiently to survive and grow". From the above definition it is comprehensible that there are many independent entities in a supply chain each of which try to maximize their own inherent objective functions (or interests) in business transactions. One of the earliest works in supply chain configuration design area was initiated by Geoffrion and Graves (1974). They described the mixed integer programming model for determining locations of distribution facility and a solution technique based on Bender's decomposition. As recent researchers Truong and Azadivar (2003) rightly mention, supply chain problems are complex and difficult to solve. The reasons could be the number of entities in the supply chain (length), the lead times at each node (Cakravastia, Toha, & Nakamura, 2002), inventory management (Giannoccaro & Pontrandolfo, 2002), logistics (Lummus, Krumwiede, & Vokurka, 2001), to mention a few. Most of the research in this area is based on the classic work of Clark and Scarf (1960), Clark and Scarf (1960, 1962). More recent discussion of two echelon models may be found in Diks, De Kok, and Lagodimos (1996). Williams (1981) presented seven heuristic algorithms for scheduling production and distribution operations in an assembly supply chain network and also he developed a dynamic programming algorithm for simultaneous determining the production and distribution batch sizes at each node within a supply chain network. Ishii, Takahashi, and Muramatsu (1988) developed deterministic model for determining the base stock levels and lead times associated with the lowest cost solutions for an integrated supply chain on a finite horizon. Cohen and Lee (1989), present a deterministic mixed integer, nonlinear mathematical programming model, based on economic order quantity techniques. Cohen and Moon (1990) extend Cohen and Lee (1989) work by developing a constrained optimization model, called PILOT, to investigate the effects of various parameters on supply chain cost and consider the additional problem of determining which manufacturing facilities and distribution centers should be open. Lee and Billington (1993) developed a supply chain model operating under a periodic review

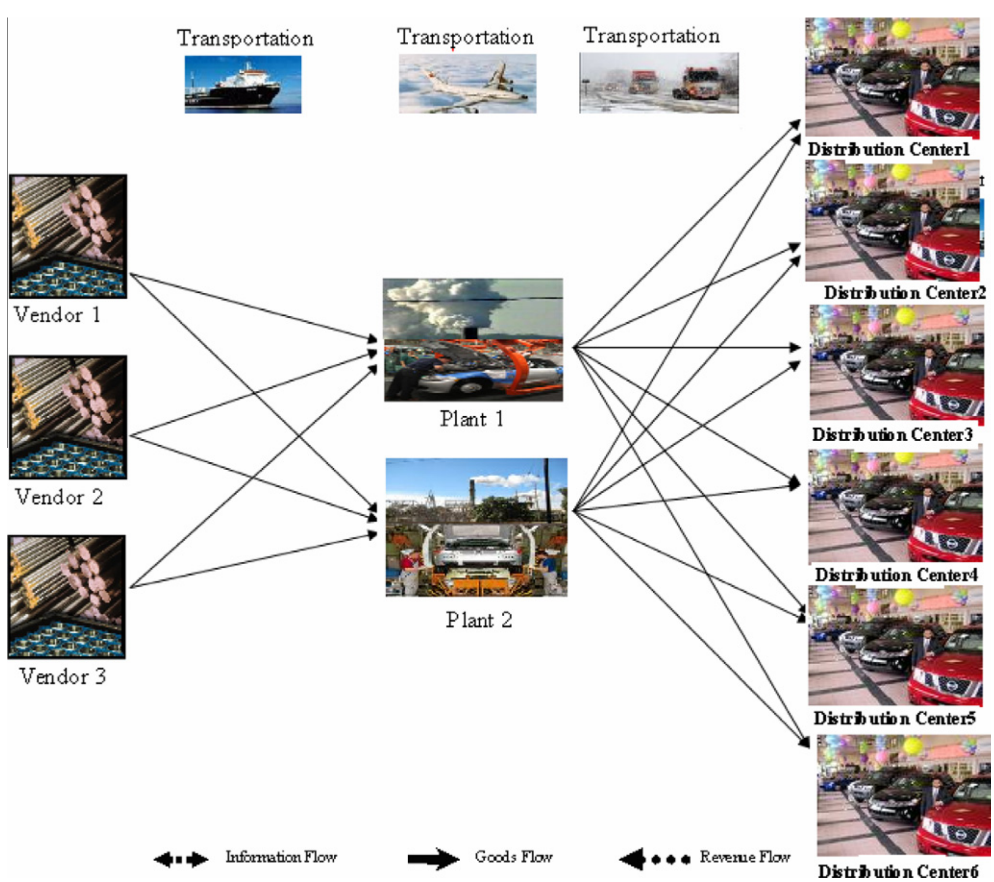

Fig. 1. Three echelon supply chain network architecture.

├ Component 1 fromV1,V2,V3 ┤ ├ Component 2 fromV1,V2,V3┤ ├ Component 3 fromV1,V2,V3┤ ├Products from P1 to All DCs┤ ├Products from P2 to All DCs┤

x_{111}	x_{112}	x_{121}	x_{122}	x_{131}	x_{132}	x_{211}	x_{212}	x_{221}	x_{222}	x_{231}	x_{232}	x_{311}	x_{312}	x_{321}	x_{322}	x_{331}	x_{332}	Y_{11}	Y_{12}	Y_{13}	Y_{14}	Y_{15}	Y_{16}	Y_{21}	Y_{22}	Y_{23}	Y_{24}	Y_{25}	Y_{26}
137	47	75	72	73	65	115	19	56	82	114	83	126	160	42	20	118	4	39	68	32	29	55	62	43	30	23	28	34	26

Fig. 2a. Particle representation in PSO algorithm for three stage SCN configuration.

Representation of swarm size = 5 particles (Decision variables)																														
Particle	x_{111}	x_{112}	x_{121}	x_{122}	x_{131}	x_{132}	x_{211}	x_{212}	x_{221}	x_{222}	x_{231}	x_{232}	x_{311}	x_{312}	x_{321}	x_{322}	x_{331}	x_{332}	Y_{11}	Y_{12}	Y_{13}	Y_{14}	Y_{15}	Y_{16}	Y_{21}	Y_{22}	Y_{23}	Y_{24}	Y_{25}	Y_{26}
1	137	47	75	72	73	65	115	19	56	82	114	83	126	160	42	20	118	4	39	68	32	29	55	62	43	30	23	28	34	26
2	149	30	61	68	88	90	109	24	98	128	91	37	142	39	60	27	99	123	60	36	31	58	63	50	36	25	29	23	29	46
3	111	58	85	48	74	90	71	31	65	150	138	14	108	20	22	122	140	53	40	51	26	39	39	75	48	19	28	43	37	20
4	60	83	30	13	244	28	39	56	222	34	83	47	214	40	26	71	93	13	48	26	92	93	42	32	20	34	4	0	13	50
5	124	23	70	74	44	108	116	13	56	34	66	158	59	78	28	108	151	20	33	60	24	35	31	55	32	19	39	63	25	27

Fig. 2b. Swarm representation in PSO algorithm for three stage SCN configuration.

Step 1: Initializing the particle position $\{X_{kd},\ d = 1,2,\ldots D\}$
Where 'k' denotes the number of particles, 'D' denotes maximum number of dimensions within the minimum and maximum limits for each dimension.

Step 2: Initialize the particle velocity $\{v_{kd},\ d=1,2,\ldots\ldots D\}$
Where 'k' denotes the number of particles, 'D' denotes maximum number of dimensions within the minimum and maximum limits for each dimension.

Step 3: Calculate the maximum velocity of the particles
$v_{max} = 0.5$ * Upper bound of the components dimensions.

Step 4: If $v_{kd}^{new} > v_{max}$
set $v_{kd}^{new} = v_{max}$ for all 'k' and 'd'.

Step 5: Evaluate $Z\{X_{kd}\}$ (function value for all particles).

Step 6: Initialize/ Update $\{P_{kd}\}$ (best point of the particle, ie particle best)and $\{G_d\}$(global best).

Step 7: Calculate new velocity v_{kd}^{new} is the PSO velocity equations.
{Use equation (3.14) For B-PSO }
{ Use equation (3.16) For LDIW-PSO }
{ Use equation (3.19) For CFM-PSO }
{ Use equation (3.22) For NLIW-PSO }
Check if
$v_{kd} > v_{max}$
set $v_{kd} = v_{max}$ for all 'k' as 'd'.

Step 8: Updated position of the particle

$$X_{kd}^{new} = v_{kd}^{new} + X_{kd}$$

Step 9: If terminate condition is not met then go back to step5
Else go to step 10.

Step10: Print $\{G_d\}$ or $Z\,\{G_d\}$
Stop

Fig. 3. General structure of optimization three stage multi echelon supply chain network architecture using PSO algorithm.

Table 1
Capacity (quantity) of vendor '*j*' for component '*i*' for SCS.

	Component 1	Component 2	Component 3
Vendor 1	200	150	400
Vendor 2	300	400	150
Vendor 3	300	250	250

Table 2
Cost of making a component '*c*' by vendor '*v*' in Rs. for SCS.

	Component 1	Component 2	Component 3
Vendor 1	300	115	90
Vendor 2	320	120	85
Vendor 3	290	125	75

Table 3
Transportation cost of a component 1 from vendor '*v*' to plant '*p*'/unit for SCS.

	Plant 1	Plant 2
Vendor 1	10	13
Vendor 2	15	17
Vendor 3	12	15

Table 4
Transportation cost of a component 2 from vendor '*v*' to plant '*p*'/unit for SCS.

	Plant 1	Plant 2
Vendor 1	6	7
Vendor 2	4	6
Vendor 3	5	7

Table 5
Transportation cost of a component 3 from vendor '*v*' to plant '*p*'/unit for SCS.

	Plant 1	Plant 2
Vendor 1	3	4
Vendor 2	5	6
Vendor 3	6	4

Table 6
Data related to plants for SCS.

	Plant 1	Plant 2
Capacity of plant '*p*'	400	300
Labor cost of plant '*p*'/unit	100	110
Manufacturing cost of plant '*p*'/unit	1800	1900
Inventory cost of plant '*p*'/unit	50	45

Table 7
Plant transportation cost (Rs/unit) for SCS.

	DC 1	DC 2	DC 3	DC4	DC 5	DC 6
Plant 1	7	12	15	17	18	20
Plant 2	12	10	11	13	15	17

Table 8
Selling price at distribution center for SCS.

	DC 1	DC 2	DC 3	DC4	DC 5	DC 6
Selling price at distribution center 'SP'/unit in Rs.	3500	3400	3700	3800	4000	3600

base stock system at Hewlett Packard, and employed a search heuristic to find the optimal inventory levels across the supply chain.

Supply chain concepts aim at coordinating the procurement of raw material, production and the distribution of final products to customers to form a single integrated process. The positive impact of optimizing the supply chain (SC) is continuously reported in the literature. Companies such as Dow Brands Inc (Robinson, Gao, & Muggenborg, 1993), Libbey–Owens–Ford (Martin, Dent, & Eckhart, 1993), General Motors (Blumenfeld, Burns, Daganzo, Frick, & Hall, 1987) and Digital Equipment Corporation (Arntzen, Brown, Harrison, & Trafton, 1995) achieved substantial cost savings through the optimization of the supply chain. Recent review papers on the supply chain design problem included by Beamon (1998), Slats, Bhola, Evers, and Dijphuizen (1995) and Thomas and Griffin (1996). Most of the reviews agree on the benefits of integrating the various echelons of the supply chain. Being aware that this leads to very complex decision problems, they emphasize the need for good analytical models and efficient solution methods to help decision-making.

Bora and Grossmann (2008) formulated the problem as a multistage stochastic program with decision dependent elements where investment strategies are considered to reduce uncertainty, and time-varying distributions are used to describe uncertainty. And proposed a new mixed-integer/disjunctive programming model. Göttlich, Herty, and Ringhofer (2009) proposed a mathematical description that captures the dynamic behavior of the system by a coupled system of ordinary differential delay equations. The underlying optimization problem was solved using discretization techniques yielding a mixed-integer programming problem. Muge and Grossmann (2008) presented a multi-period mixed integer linear programming model for the simultaneous planning and scheduling of single-stage multi-product continuous plants with parallel units. Zhang, Zhang, Cai, and Huang (2011) presented a new manufacturing resource allocation method using extended genetic algorithm (GA) to support the multi-objective decision-making optimization for supply chain deployment. A new multi-objective decision-making mathematical model is proposed to evaluate, select, and sequence the candidate manufacturing resources allocated to sub-tasks composing the supply chain, by dealing with the trade-offs among multiple objectives including similarity, time, cost, quality, and service. David, Mula, Poler, and Lario (2009) presented a review of the literature related to supply chain planning methods under uncertainty. The main objective is to provide the reader with a starting point for modeling supply chain under uncertainty applying quantitative approaches. Srinivas and Rao (2010) have developed four consignment stock inventory models of supply chain. The lead time is assumed to be dependent because, at the time of contract with the manufacturer, the retailer may intend to reduce the lead time for which the retailers pay an additional cost. Ene and Öztürk (2011), the objective of his study was to design storage assignment and order picking system using a developed mathematical model and stochastic evolutionary optimization approach in the automotive industry. It is performed in two stages. At the first stage, storage location assignment problem is solved with a class-based storage policy with the aim of minimizing warehouse transmissions by using integer programming. At the second stage, batching and routing problems are considered together to minimize travel cost in warehouse operations. Iraj, Amin, Mahdi Paydar, and Solimanpur (2011) presented a fuzzy goal programming-based approach for solving a multi-objective mathematical model of cell formation problem and production planning in a dynamic virtual cellular manufacturing system (Victor Raj, Sankar, & Ponnambalam, 2011). In this work, a particle swarm optimization based algorithm is proposed by applying the batch selective assembly methodology to a multi-characteristic assembly environment, to maximize the assembly efficiency and thereby maximizing the manufacturing system efficiency. The proposed algorithm is tested with a set of experimental problem data sets and is found to outperform the traditional selective assembly and sequential assembly methods, in producing solutions with higher manufacturing system efficiency. Dat, Truc, Doan, Chou, and Yu (2012) this paper presents a mathematical programming model which minimizes the total processing cost of multiple types of electrical and electronic products (EEPs). Based on the proposed model, the optimal facility locations and the material flows in the reverse logistic network can be determined. (Alev & Ali, 2009) In this paper, for effective multi-echelon supply chains under stochastic and fuzzy environments, an inventory management framework and deterministic/stochastic-neuro-fuzzy cost models within the context of this framework are structured. Chen and Chien (2011) have evolved with a new method, called the genetic simulated annealing ant colony system with particle swarm optimization techniques, for solving the traveling salesman problem.

The Particle Swarm Optimization (PSO) method is a member of the wide category of Swarm Intelligence methods (Kennedy & Eberhart, 2001) for solving Global Optimization problems. It was originally proposed by Kennedy as a simulation of social behavior, and it was initially introduced as an optimization method in 1995 (Eberhart & Kennedy, 1995). PSO is related with Artificial Life, and specifically to swarming theories, and also with EC (Evolutionary computation), especially evolutionary strategies (ES) and genetic algorithm (GA). PSO can be easily implemented and it is computationally in expensive, since its memory and CPU speed requirements are low. Moreover, it does not require gradient information of the objective function under consideration, but only its values, and it uses only primitive mathematical operators. PSO has been proved to be an efficient method for many GO problems and in some cases it does not suffer the difficulties encountered by other EC techniques (Eberhart & Kennedy, 1995). Velocity updates in PSO can also be clamped with a user defined maximum velocity ($V_{\max}$), which would prevent them from exploding, thereby causing premature convergence. Some of the first applications of PSO were to train neural networks (NNs). Results have shown that PSO is better than GA. PSO is easy to implement and has been successfully applied to solve a wide range of optimization problems such as continuous nonlinear and discrete optimization problems (Kennedy & Eberhart, 1995; Eberhart & Shi, 1998). Guillen, Badell, Espuna, and Puigjaner (2006) addresses the integrated planning/scheduling of chemical supply chains(sc) with multi-product, multi-echelon distribution networks taking into account financial management issues. Cardenas-Barron (2006) have proposed n-stage-multi customer supply chain inventory model and they have considered a simple supply chain configuration for finding the optimal equal cycle time and the optimal total annual cost by using algebraic procedure. Hasksever and Moussourakis (2005) proposed mixed integer programming model to optimize the two fundamental decisions of inventory management for ordering multiple inventory items subject to multiple resource constraints. Daskin and Shen (2005) proposed mathematical model to determine the trade-offs between customer service and cost in integrated supply chain design. They have used weighting method to find all supported points on the trade-off curve and also proposed a heuristic solution approach based on GA that can generate optimal or close to optimal solutions.

The literature survey indicates that the PSO algorithm is found to be quite powerful by various researchers to find the minimum of a numerical function on a continuous definition domain and very little research has been carried out to implement PSO algorithm in a discrete combinatorial optimization problem such as flow shop scheduling. No literature is found till date, the PSO algorithm (except our work) applications in multi echelon supply chain network optimization. Hence, we tackled above multi-echelon challenges and issues highlighted in the last paragraph of the introduction section by new optimizer particle swarm optimization as the computers have become more powerful in terms of computational speed to handle combinatorial NP hard problems.

In this work, different variations of particle swarm optimization algorithms are used for solving constrained multi echelon supply chain network problems with the objective of minimizing total supply chain operating cost (TSCC). The performances of the PSO variants used in this research study have been compared with genetic algorithm.

3. Problem definition, model description and mathematical formulation

This section briefly describes the objective of study, model assumptions, problem description and the mathematical formulations of the three stage multi echelon supply chain network model.

3.1. Objectives of study

This paper specifically deals with the modeling and optimization of a three stage multi echelon supply chain network architecture using the new particle swarm optimization algorithms. Total supply chain operating cost (TSCC) of the supply chain network is considered as a performance indicator.

Supply chain network architecture consists of many stages or echelons. In this research, the supply chain architecture consists of three echelons (stages), i.e. vendors, manufacturing plants, and dealers in order of their contributions to the chain. Each supply chain echelon has a set of control parameters that affect the performance of other components. This work considers a constrained objective problem formulation for a pull based supply chain architecture and proposes the PSO algorithms for solving the constraint optimization problem. The performance of the each echelon will be optimized simultaneously at tactical level planning. It optimizes material flows throughout the supply chain, gives the optimal procurement, production and distribution scheduling plans.

3.2. Model assumptions

- Problem is tactical or snaps shot pull based problem.
- A single product flows through the supply chain network.
- A product is made up of three components.
- Distribution centers face random customer demand and demand distribution is assumed to be uniform.
- Quantity of goods at every installation takes integer values.
- Linear holding cost rates exist only for manufacturing plants in the supply chain.
- Shortages are not permitted (no shortage cost).
- Transportation costs are directly proportional to the quantity shipped.
- Manufacturing costs are directly proportional to the quantity of products produced.
- All installations have finite capacity.

3.3. Problem description

A general three stage multi echelon supply chain consists of three different levels of enterprises as shown in Fig. 1. The first level enterprise is distribution center or market from which the products are sold to retailers. The second level enterprise is plant or manufacturer and products are manufactured as per the requirements of the distribution centers and uses different types of transport to deliver products from plant side to distribution center. Third level enterprise is vendor, where raw material components are procured from different vendors for manufacturing of products.

The proposed model attempts to capture the dynamics of a single product being manufactured out of three different components. These three different components are needed to manufacture a final product and can be supplied by any of the three vendors. These components can be shipped to any of the two plants, where the product is made. Then the products are being shipped to distribution centers (DCs) based on the demand.

3.4. The mathematical formulation of three stage multi echelon supply chain architecture

This section develops a mathematical model to quantify the relationship among all the decision variables involved in three stage multi echelon supply chain network. Total supply chain operating cost (TSCC) of the supply chain network is used as the performance indicator of the proposed model. The problem of optimizing the supply chain configuration can be summarized in the following mathematical model.

The notations used in the formulation of mathematical model are shown below:

Notation	Description
C	number of components
V	number of vendors
P	number plants
D	number distribution centers
$L_{c,v}$	capacity of vendor 'v' for component 'c'
$\mathrm{CS}_{c,v}$	cost of making a component 'c' by vendor 'v'
$\mathrm{STC}_{c,v,p}$	transportation cost of a component 'c' from vendor 'v' to plant 'p'/unit
U_p	capacity of plant 'p'
MC_p	manufacturing cost of plant 'p'/unit
IC_p	inventory cost at plant 'p'/unit/period
$I_{c,p}$	inventory of component 'c' at plant 'p'
$\mathrm{PTC}_{p,d}$	plant transportation cost from plant 'p' to distribution center 'd'
D_d	demand at distribution centers 'd'
SP_d	selling price at distribution center 'd'/unit
$X_{c,v,p}$	amount of component shipped 'c' from vendor 'v' to plant 'p'
$Y_{p,d}$	amount of product shipped from plant 'p' to distribution center 'd'
TSCC	total supply chain operating cost

The objective function, the total supply chain operating cost (TSCC) of supply chain network (Eq. (1)), consists of three components (Eqs. (2)–(4)). The first component is Total Supplier Material Cost (TSMC) involved in purchasing components from all the vendors for manufacturing. The second component is the total manufacturing cost incurred at plants (TMC) consists of total labor, machining and inventory carrying costs. The third part is the total transportation cost (TTC) consists of transportation cost in purchasing components from vendors and shipping costs of finished goods from plants to the respective distribution centers to meet the demand.

Table 9
Results of performance evaluation – TSCC by Basic PSO Algorithm (B-PSO) for SCS.

SR	Feasible solutions																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Best	Worst	Mean	STD
1	1308259	1321373	1334392	1336379	1255202	1257014	1278616	1263894	1300245	1239683	1316411	1237224	1283787	1295929	1239776	1237224	1336379	1284546	34661
2	1338346	1311171	1257689	1338133	1350306	1280311	1317487	1351748	1340417	1340481	1341072	1299518	1298658	1320702	1315558	1257689	1351748	1320106	27136
3	1266307	1240249	1304902	1235795	1236078	1288122	1285779	1262752	1326919	1278397	1299687	1252902	1251911	1246353	1287323	1235795	1326919	1273715	27759
4	1194676	1240895	1257395	1226060	1298006	1186917	1234636	1279606	1240748	1296931	1286523	1266536	1237869	1244023	1279486	1186917	1298006	1251354	33899
5	1237501	1157844	1248409	1243116	1255385	1176455	1249263	1212453	1192054	1215714	1171023	1146509	1284950	1213393	1225362	1146509	1284950	1215295	39759
6	1235289	1270248	1252093	1297390	1223881	1222183	1260634	1245800	1227379	1325291	1207581	1244371	1245342	1271288	1222079	1207581	1325291	1250057	31315
7	1293486	1239588	1254638	1247422	1282072	1278919	1242966	1259805	1298422	1306055	1282172	1287117	1257575	1274621	1294028	1239588	1306055	1273259	21423
8	1264854	1200152	1221323	1171294	1128104	1124049	1154078	1139545	1266966	1203827	1184209	1210237	1182355	1160601	1179340	1124049	1266966	1186062	43438
9	1267626	1185648	1233164	1201554	1284907	1202832	1242819	1191510	1223961	1232059	1234033	1175358	1217756	1245975	1171137	1171137	1284907	1220689	32964
10	1116584	1199239	1122063	1119147	1168778	1145941	1156481	1160073	1138273	1169836	1178688	1189586	1182938	1149212	1115381	1115381	1199239	1154148	27688
11	1205195	1173756	1187500	1213645	1175832	1188895	1218973	1201868	1164995	1176515	1136741	1169934	1185138	1238831	1196424	1136741	1238831	1188949	24959
12	1235209	1212929	1169278	1193184	1220849	1172275	1243802	1244505	1189145	1210130	1236880	1208082	1209219	1232834	1182322	1169278	1244505	1210710	25215
13	1286925	1306562	1264508	1325700	1268635	1280385	1279350	1288571	1266950	1311624	1218180	1359973	1328375	1343519	1283646	1218180	1359973	1294194	35896
14	1246715	1185817	1187866	1191741	1209334	1177437	1258271	1193634	1172471	1183722	1183079	1245289	1202556	1211951	1239631	1172471	1258271	1205968	28255
15	1294914	1260189	1289428	1289759	1293435	1253928	1231507	1277052	1307050	1289348	1306481	1281109	1248939	1300608	1263200	1231507	1307050	1279130	22680
16	1132238	1189436	1097955	1102094	1141261	1113543	1117835	1086702	1132427	1125966	1059990	1177878	1130269	1090389	1067839	1059990	1189436	1117721	36007
17	1131200	1129421	1171670	1156418	1101776	1133816	1099870	1186050	1100680	1146823	1141685	1170486	1148241	1150528	1097225	1097225	1186050	1137726	28218
18	1160402	1141659	1092879	1102699	1183793	1083230	1092631	1052951	1092699	1141340	1149734	1097227	1102527	1194016	1134282	1052951	1194016	1121471	39965
19	1105205	1082737	1096558	1087828	1072411	1069278	1158365	1155867	1093749	1147783	1123842	1072376	1126579	1102907	1129415	1069278	1158365	1108327	30369
20	1189834	1254996	1220268	1262613	1223638	1249559	1253222	1279806	1210285	1258730	1274874	1251803	1317545	1241346	1242882	1189834	1317545	1248760	30732

Table 10
Results of performance evaluation – TSCC by Linearly decreasing inertia weight PSO algorithm (LDIW-PSO) for SCS.

SR	Feasible solutions																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Best	Worst	Mean	STD
1	1294322	1213922	1204475	1181150	1217887	1194813	1186276	1240294	1251224	1208524	1186637	1251274	1207511	1183957	1210416	1181150	1294322	1215512	31557
2	1261926	1237686	1243018	1256454	1228269	1344791	1231960	1229778	1312056	1221542	1283370	1227830	1252680	1254207	1244899	1221542	1344791	1255364	34290
3	1238936	1187034	1245300	1157120	1189921	1176360	1179038	1244204	1242505	1242438	1170462	1278526	1272524	1230669	1260373	1157120	1278526	1215462	38168
4	1158164	1199747	1187959	1249872	1177306	1229118	1192357	1185155	1189543	1216677	1172155	1192096	1201299	1243292	1254568	1158164	1254568	1203287	29205
5	1122517	1205904	1134249	1159612	1186016	1149515	1160201	1163594	1205561	1173476	1103279	1123506	1147803	1236976	1130033	1103279	1236976	1160149	36600
6	1183619	1187698	1189824	1168241	1258109	1172489	1189475	1139760	1176344	1152566	1249220	1190025	1202042	1151320	1229581	1139760	1258109	1189354	34107
7	1191240	1255602	1200495	1231662	1233528	1208445	1252466	1231362	1213087	1262374	1234214	1283267	1216434	1276022	1203218	1191240	1283267	1232894	28155
8	1151225	1102189	1085906	1132262	1146454	1188867	1075470	1093954	1104511	1098084	1162640	1098127	1117855	1107814	1129829	1075470	1188867	1119679	31593
9	1116121	1201870	1214860	1150221	1118333	1168981	1297762	1109366	1143215	1136059	1238145	1093073	1119103	1127488	1147326	1093073	1297762	1158795	56348
10	1212614	1075440	1082913	1117067	1110646	1143611	1057618	1132694	1168001	1078789	1105850	1080191	1106335	1054250	1171809	1054250	1212614	1113189	45458
11	1074848	1212844	1081046	1103935	1076725	1137735	1094178	1115529	1179554	1179554	1073381	1123438	1177188	1092963	1111719	1073381	1212844	1122309	45180
12	1138467	1169228	1109026	1191252	1153436	1121914	1140405	1131111	1211344	1118687	1120084	1162237	1114285	1120454	1141847	1109026	1211344	1142918	29742
13	1213288	1199886	1204290	1316921	1194339	1221290	1196388	1195774	1192317	1223718	1341378	1323758	1254973	1194643	1222638	1192317	1341378	1233040	51752
14	1119981	1127086	1095752	1081595	1186674	1114435	1149620	1150081	1112654	1101594	1106911	1115002	1125100	1140579	1127599	1081595	1186674	1123644	25730
15	1168441	1243391	1203288	1167940	1179741	1193138	1214158	1224647	1210825	1192429	1190462	1282472	1188248	1198947	1206225	1167940	1282472	1204290	29462
16	1011148	1056138	1000651	1129600	1028944	1090289	1051204	1034365	1016996	1020432	1013107	1032049	1047917	1094947	1032499	1000651	1129600	1044019	35929
17	1031684	1062384	1093292	1024067	1089930	1031252	1049246	1044222	1064225	1095351	1023827	1055588	1179886	1128037	1140242	1023827	1179886	1074216	46521
18	1108853	1013262	1029543	1006582	1145822	1036233	1105783	1040271	1074021	1057240	1004767	1075291	1128334	1020003	1069598	1004767	1145822	1061040	45199
19	1015418	1057481	998636	994973	1075737	1050747	1014706	1167300	1014035	1012591	987198	1027454	1095382	1050908	1037404	987198	1167300	1039998	46637
20	1261632	1181492	1245781	1134732	1196432	1258944	1243936	1147092	1185427	1230198	1224638	1172563	1202156	1163968	1196230	1134732	1261632	1203015	39981

Table 11
Results of performance evaluation – TSCC by construction factor PSO algorithm (CFM-PSO) for SCS.

SR	Feasible solutions																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Best	Worst	Mean	STD
1	1169865	1204684	1231465	1193797	1177205	1173237	1220674	1202149	1201299	1234624	1214600	1171159	1181491	1185400	1213949	1169865	1234624	1198373.2	21684
2	1209727	1225100	1230184	1223905	1242915	1225375	1214713	1224713	1231794	1230655	1236750	1238846	1213873	1230835	1219067	1209727	1242915	1226563.5	9459
3	1183842	1160507	1201495	1216415	1192474	1195521	1198682	1196191	1181040	1220709	1177984	1204829	1185707	1213602	1168469	1160507	1220709	1193164.5	17247
4	1130775	1144241	1176003	1150043	1175678	1128442	1157600	1160545	1142809	1153750	1167279	1172492	1155698	1147431	1163888	1128442	1176003	1155111.6	14838
5	1138081	1129488	1113099	1132629	1140798	1108104	1116439	1165043	1124611	1126421	1161556	1111748	1116268	1142910	1131486	1108104	1165043	1130578.7	17091
6	1141072	1136486	1138387	1182857	1171082	1138044	1135450	1189311	1166903	1170279	1138314	1162119	1136737	1163384	1150594	1135450	1189311	1154734.6	18556
7	1189876	1200212	1184643	1168294	1201367	1187071	1192503	1269526	1189917	1179612	1198956	1171802	1197084	1188472	1184076	1168294	1269526	1193560.7	23129
8	1110461	1096928	1141498	1079826	1079731	1143922	1100356	1128830	1084590	1101591	1116364	1081473	1119363	1090297	1079753	1079731	1143922	1103665.5	22277
9	1146722	1189030	1117349	1126031	1129844	1131794	1101482	1123475	1138291	1146237	1125363	1134022	1098622	1110414	1110817	1098622	1189030	1128632.9	22164
10	1066337	1099251	1102499	1080932	1119877	1091855	1041934	1062165	1065770	1089166	1106314	1078989	1072881	1077642	1079302	1041934	1119877	1082327.6	19852
11	1086903	1060454	1093188	1071855	1093598	1099515	1095512	1144817	1113044	1068049	1089608	1078852	1128810	1084975	1118059	1060454	1144817	1095149.3	23020
12	1110012	1119719	1147433	1137630	1135634	1103561	1114255	1116564	1142398	1106364	1123282	1121284	1114175	1109418	1119955	1103561	1147433	1121445.6	13462
13	1196842	1195991	1189419	1204980	1208316	1201010	1186463	1189621	1213113	1191155	1182224	1193110	1196398	1191696	1188922	1182224	1213113	1195284	8488
14	1110270	1116870	1081836	1147156	1148309	1140672	1098132	1099352	1119165	1155708	1099937	1154506	1130307	1078179	1115356	1078179	1155708	1119717	25602
15	1190498	1175031	1192145	1160656	1172741	1166809	1198836	1195396	1215136	1173312	1213622	1186919	1190021	1195463	1173194	1160656	1215136	1186651.9	16157
16	1044528	1055696	1092805	1003538	1112081	1064750	1061147	1020530	1054307	1037418	1045513	1010777	1033924	1014911	1056306	1003538	1112081	1047215.4	29600
17	1100444	1057124	1057122	1156164	1085294	1056309	1047591	1072909	1076968	1061083	1052873	1063554	1024629	1055288	1053382	1024629	1156164	1068048.9	29966
18	1020640	1040118	1048525	1002379	1087722	1067716	1013436	1065236	1074645	1018815	1031200	1019846	1057578	1009093	1006728	1002379	1087722	1037578.5	27603
19	1000700	1034739	1002225	981119	1018038	1043971	1002199	1021724	1005156	1062718	1049814	1030841	1055924	1029054	1029943	981119	1062718	1024544.3	23190
20	1170461	1198255	1148950	1182169	1153575	1182671	1148954	1155094	1151446	1158913	1160213	1166865	1185719	1182387	1189879	1148950	1198255	1169036.7	16561

Table 12
Results of performance evaluation – near optimal TSCC by non linear inertia weight PSO algorithm (NLIW-PSO) for SCS.

SR	Feasible solutions																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Best	Worst	Mean	STD
1	1182312	1196861	1180997	1177133	1172681	1179147	1185654	1189341	1168932	1190741	1177294	1172813	1204320	1186286	1166627	1166627	1204320	1182076	10401
2	1220247	1227258	1222435	1236524	1209032	1229285	1225961	1223815	1214459	1218456	1222763	1212803	1215312	1226859	1212083	1209032	1236524	1221153	7524
3	1165313	1173016	1168253	1175597	1177560	1172997	1167316	1181420	1169126	1175364	1175060	1158374	1199908	1170932	1155789	1155789	1199908	1172402	10248
4	1131447	1136432	1135887	1134974	1142144	1150485	1144265	1140242	1131214	1136486	1146565	1131664	1196815	1130757	1123155	1123155	1196815	1140835	17008
5	1107802	1129190	1114859	1106791	1152005	1112870	1113614	1111711	1104358	1114153	1113885	1106842	1113819	1102480	1100947	1100947	1152005	1113688	12589
6	1133539	1136676	1145958	1135317	1138096	1144570	1138006	1155718	1134034	1134223	1136260	1138764	1143120	1127205	1127864	1127205	1155718	1137957	7213
7	1208779	1182790	1180892	1175658	1173998	1188105	1181465	1182586	1173236	1176819	1180925	1177272	1177257	1174016	1171024	1171024	1208779	1180321	9074
8	1068508	1081449	1100823	1075685	1072924	1085818	1097936	1080861	1094329	1088332	1073415	1073405	1099324	1070600	1086548	1068508	1100823	1083330	10996
9	1094016	1103818	1096995	1099231	1093218	1106047	1107574	1100560	1101310	1116240	1112972	1091580	1140055	1087377	1120514	1087377	1140055	1104767	13492
10	1045507	1057741	1057179	1057259	1072785	1057798	1057070	1057783	1049561	1073279	1054981	1048537	1077306	1043365	1047693	1043365	1077306	1057190	10224
11	1060482	1075638	1059993	1067315	1085072	1068931	1066090	1068925	1060796	1084373	1065372	1070069	1058741	1055309	1056639	1055309	1085072	1066916	9125
12	1109065	1099694	1102486	1103175	1112809	1105037	1100797	1099578	1103733	1099228	1099628	1092194	1094606	1093123	1096846	1092194	1112809	1100800	5613
13	1189855	1186691	1181263	1187029	1177268	1187903	1187046	1188533	1182890	1186988	1188013	1176465	1189174	1181362	1174379	1174379	1189855	1184324	5045
14	1079209	1093242	1078919	1090856	1129897	1082049	1082008	1092157	1082707	1085850	1074433	1074353	1073182	1075740	1068645	1068645	1129897	1084216	14570
15	1163851	1180342	1162528	1166775	1186651	1181777	1175880	1169935	1170025	1173496	1166569	1159934	1171299	1161184	1166561	1159934	1186651	1170454	7906
16	997122	1021755	1009707	1004570	1005338	1006804	1007058	1008363	1014339	1004164	1009322	997968	1034570	998080	1006170	997122	1034570	1008355	9617
17	1020231	1027584	1019287	1025009	1035465	1032198	1021686	1026602	1023036	1018885	1022852	1021847	1020205	1010813	1031571	1010813	1035465	1023818	6206
18	1001337	1004593	1006680	1003633	998072	1011927	1004179	1007774	1012449	1012553	1017017	995907	1012614	997724	1023950	995907	1023950	1007361	7786
19	983758	991301	984423	985709	1001538	990372	984074	986175	984585	984044	986435	978236	1007880	1018840	974146	974146	1018840	989434	11610
20	1143793	1151996	1139856	1150111	1141501	1143256	1153278	1157854	1145531	1142007	1149155	1135725	1146683	1132332	1162343	1132332	1162343	1146361	8022

Table 13
Performance evaluation – best TSCC value and relative percentage increase in TSCC of three echelon SCN yielded by PSO variants and GA for SCS.

SR	Best TSCC of each scenarios yielded by heuristic procedures for the 3-echelon supply chain network					Relative percentage increase in best TSCC value				
	GA	B-PSO	LDIW-PSO	CFM-PSO	NLIW-PSO	GA	B-PSO	LDIW-PSO	CFM-PSO	NLIW-PSO
1	1345621	1237224	1181150	1169865	1166627	15.34	6.05	1.24	0.28	0
2	1363457	1257689	1221542	1209727	1209032	12.77	4.02	1.03	0.06	0
3	1247364	1235795	1157120	1160507	1155789	7.923	6.92	0.12	0.41	0
4	1293452	1186917	1158164	1128442	1123155	15.16	5.68	3.12	0.47	0
5	1247645	1146509	1103279	1108104	1100947	13.32	4.14	0.21	0.65	0
6	1309467	1207581	1139760	1135450	1127205	16.17	7.13	1.11	0.73	0
7	1283567	1239588	1191240	1168294	1171024	9.867	6.10	1.96	0.00	0.23
8	1235464	1124049	1075470	1079731	1068508	15.63	5.20	0.65	1.05	0
9	1278654	1171137	1093073	1098622	1087377	17.59	7.70	0.52	1.03	0
10	1222345	1115381	1054250	1041934	1043365	17.32	7.05	1.18	0.00	0.14
11	1238746	1136741	1073381	1060454	1055309	17.38	7.72	1.71	0.49	0
12	1273245	1169278	1109026	1103561	1092194	16.58	7.06	1.54	1.04	0
13	1292435	1218180	1192317	1182224	1174379	10.05	3.73	1.53	0.67	0
14	1278655	1172471	1081595	1078179	1068645	19.65	9.72	1.21	0.89	0
15	1286467	1231507	1167940	1160656	1159934	10.91	6.17	0.69	0.06	0
16	1164533	1059990	1000651	1003538	997122	16.79	6.30	0.35	0.64	0
17	1199857	1097225	1023827	1024629	1010813	18.7	8.55	1.29	1.37	0
18	1155436	1052951	1004767	1002379	995907	16.02	5.73	0.89	0.65	0
19	1074353	1069278	987198	981119	974146	10.29	9.77	1.34	0.72	0
20	1293245	1189834	1134732	1148950	1132332	14.21	5.08	0.21	1.47	0

Note: SR, simulation run; GA, genetic algorithm; B-PSO, standard particle swarm optimization algorithm; LD-PSO, linearly decreasing inertia weight particle swarm optimization algorithm; CFM-PSO, construction factor method particle swarm optimization algorithm; NLIW-PSO, non-linear inertia weight particle swarm optimization algorithm; TSCC, total supply chain operating cost.

3.5. Objective function

The objective function is given by

Minimize TSCC = TSMC + TMC + TTC

$$\begin{aligned}\mathrm{TSCC} = &\left[\sum_c \sum_v \sum_p (\mathrm{CS}_{c,v} \times X_{c,v,p})\right] \\ &+ \left[\sum_p \left\{(\mathrm{MC}_p) \times \left(\sum_d Y_{p,d}\right)\right\} + \sum_p \left\{(\mathrm{IC}_p) \times \left(\sum_d I_{c,p}\right)\right\}\right] \\ &+ \left[\sum_c \sum_v \sum_p (X_{c,v,p} \times \mathrm{STC}_{c,v,p}) + \sum_p \sum_d (Y_{p,d} \times \mathrm{PTC}_{p,d})\right]\end{aligned} \tag{1}$$

The following are the three Total Supply chain cost components:

(a) Total supplier material cost:

$$\mathrm{TSMC} = \sum_c \sum_v \sum_p (\mathrm{CS}_{c,v} \times X_{c,v,p}) \tag{2}$$

(b) Total manufacturing cost:

$$\begin{aligned}\mathrm{TMC} = &\sum_p \left\{(\mathrm{MC}_p) \times \left(\sum_d Y_{p,d}\right)\right\} \\ &+ \sum_p \left\{(\mathrm{IC}_p) \times \left(\sum_c I_{c,p}\right)\right\}\end{aligned} \tag{3}$$

(c) Total Transportation cost:

$$\begin{aligned}\mathrm{TTC} = &\sum_c \sum_v \sum_p (X_{c,v,p} \times \mathrm{STC}_{c,v,p}) + \sum_p \\ &\times \sum_d (Y_{p,d} \times \mathrm{PTC}_{p,d})\end{aligned} \tag{4}$$

The profit and revenue calculations are given in Eqs. (5) and (6).

(d) Profit:

$$\mathrm{PROF} = \sum_d (D_d \times \mathrm{SP}_d) - \mathrm{TSCC} \tag{5}$$

(e) Revenue:

$$\mathrm{REV} = \sum_d (D_d \times \mathrm{SP}_d) \tag{6}$$

The problem has been formulated as constrained optimization network problem. The constraints involved in the problem are as follows:

(f) Vendor capacity constraint:

$$\sum_p X_{c,v,p} \leqslant L_{(c,v)} \quad \forall\, c, v \tag{7}$$

(g) Plant capacity constraint:

$$\sum_p Y_{p,d} \leqslant U_p \quad \forall\, p \tag{8}$$

(h) Demand constraint:

$$\sum_p Y_{p,d} \geqslant D_d \quad \forall\, d \tag{9}$$

(i) Inventory balancing constraint at plants:

$$\sum_v X_{c,v,p} - \sum_d Y_{p,d} \geqslant 0 \quad \forall\, c, p \tag{10}$$

The Eqs. (7)–(10) of the three echelon SCN model represent, respectively. Eq. (7) ensures that the required quantities of raw materials are within the supplier's capabilities.

Eq. (8) specifies that the total production quantities do not exceed plant capacities individually.

Eq. (9) ensures the products shifted from plant to distribution centers should be more than or equal to the demand so as to meet the demand of distribution center.

Eq. (10) ensures that the components shifted from the vendors should be more than the products to be manufactured to meet the demand.

3.6. Constraint handling

Transformation methods are the simplest and most popular optimization methods of handling constraints. The constrained

Table 14
Performance evaluation – matrix of outperforming Best TSCC instances of solution methodologies yielded by PSO variants and GA for SCS-I.

	GA	B-PSO	LDIW-PSO	CFM-PSO	NLIW-PSO
GA	–	0	0	0	0
B-PSO	20	–	0	0	0
LDIW-PSO	20	20	–	07	0
CF-PSO	20	20	13	–	02
NLIW-PSO	20	20	20	18	–

problem is transformed into a sequence of unconstrained problems by adding penalty terms for each constraint violation, if a constraint is violated at any point, the objective function is penalized by an amount depending on the extent of constraint violation. Penalty terms vary in the way the penalty is assigned. Here the exterior penalty method is used to handle the constraints of the problem. This kind of penalty method penalizes infeasible points but does not penalize feasible points. In these methods, every sequence of unconstrained optimization finds an improved yet infeasible solution.

This penalty parameter approach is a popular constraint handling strategy. Minimization of all objective functions is assumed here. However, a maximization function can be handled by converting it into a minimization function by using the duality principle. Thereafter, all constraint violations are added together to get the overall constraint violation which is denoted by the 'Ω' called penalty term.

$$\Omega\left(x^{(i)}\right) = \sum_{k=0}^{n} \omega_i^{\left(x^{(i)}\right)} \tag{11}$$

This constraint violation is then multiplied with a penalty parameter R_m and the product is added to each of the objective function values:

$$F_m\left(x^{(i)}\right) = f_m\left(x^{(i)}\right) + R_m \Omega\left(x^{(i)}\right) \tag{12}$$

The function F_m takes into account the constraint violations. For a feasible solution, the corresponding Ω term is zero and F_m becomes equal to the original objective function F_m. However, for an infeasible solution, $F_m > f_m$, thereby adding a penalty corresponding to total constraint violation.

Table 15
Performance evaluation – mean TSCC value and relative percentage increase in TSCC of three echelon SCN yielded by PSO variants and GA for SCS.

SR	Mean TSCC of each scenarios yielded by heuristic procedures for the 3-echelon supply chain network					Relative percentage increase in Mean TSCC value				
	GA	B-PSO	LDIW-PSO	CFM- PSO	NLIW-PSO	GA	B-PSO	LDIW-PSO	CFM- PSO	NLIW-PSO
1	1434566	1284545.6	1215512	1198373	1182076	21.36	8.67	2.83	1.38	0
2	1567434	1320106.5	1255364	1226563	1221153	28.36	8.10	2.80	0.44	0
3	1324675	1273715.2	1215462	1193164	1172402	12.99	8.64	3.67	1.77	0
4	1324565	1251353.8	1203287	1155112	1140835	16.1	9.69	5.47	1.25	0
5	1432566	1215295.4	1160149	1130579	1113688	28.63	9.12	4.17	1.52	0
6	1378543	1250056.6	1189354	1154735	1137957	21.14	9.85	4.52	1.47	0
7	1367587	1273259.1	1232894	1193561	1180321	15.87	7.87	4.45	1.12	0.00
8	1245832	1186062.3	1119679	1103666	1083330	15	9.48	3.36	1.88	0
9	1384353	1220689.3	1158795	1128633	1104767	25.31	10.49	4.89	2.16	0
10	1235687	1154148	1113189	1082328	1057190	16.88	9.17	5.30	2.38	0.00
11	1253765	1188949.5	1122309	1095149	1066916	17.51	11.44	5.19	2.65	0
12	1432876	1210709.5	1142918	1121446	1100800	30.17	9.98	3.83	1.88	0
13	1346234	1294193.5	1233040	1195284	1184324	13.67	9.28	4.11	0.93	0
14	1394532	1205967.6	1123644	1119717	1084216	28.62	11.23	3.64	3.27	0
15	1396545	1279129.8	1204290	1186652	1170454	19.32	9.28	2.89	1.38	0
16	1276543	1117721.5	1044019	1047215	1008355	26.6	10.85	3.54	3.85	0
17	1276789	1137725.9	1074216	1068049	1023818	24.71	11.13	4.92	4.32	0
18	1256897	1121471.3	1061040	1037578	1007361	24.77	11.33	5.33	3.00	0
19	1255543	1108326.7	1039998	1024544	989434	26.9	12.02	5.11	3.55	0
20	1354365	1248760.1	1203015	1169037	1146361	18.14	8.93	4.94	1.98	0

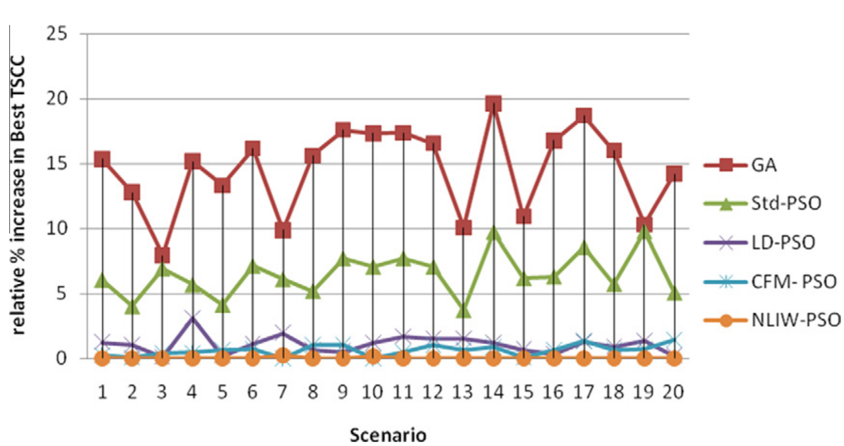

Fig. 4. Performance evaluation – relative % increase in Best TSCC for each scenario of SCS yielded by heuristics.

3.7. Modified Objective function of constrained three stage multi echelon supply chain architecture

After applying the penalty function approach to the constrained three echelon supply chain network architecture problem, the objective function is expressed as follows:

$$\text{Minimize TSCC} = \left\{ \begin{array}{l} \left[\sum_c \sum_v \sum_p (\mathrm{CS}_{c,v} \times X_{c,v,p})\right] + \\ \left[\sum_p \left\{(\mathrm{MC}_p) \times \left(\sum_d Y_{p,d}\right)\right\} + \sum_p \left\{(\mathrm{IC}_p) \times \left(\sum_c I_{c,p}\right)\right\}\right] + \\ \left[\sum_c \sum_v \sum_p (X_{c,v,p} \times \mathrm{STC}_{c,v,p}) \times \sum_p \sum_d (Y_{p,d} \times \mathrm{PTC}_{p,d})\right] \end{array} \right\}$$
$$+ R_m * \left\{ \begin{array}{l} \left[\sum_p X_{c,v,p} \leqslant L_{(c,v)}\right] + \left[\sum_p Y_{p,d} \leqslant U_p\right] + \\ \left[\sum_p Y_{p,d} \geqslant D_d\right] + \left[\sum_v X_{c,v,p} - \sum_d Y_{p,d} \geqslant 0\right] \end{array} \right\} \quad (13)$$

4. Optimization of three stage multi-echelon supply chain architecture using pso algorithms

4.1. Introduction

This section discusses particle representation in PSO, velocity calculation of all PSO algorithms and general structure of optimization of three echelon supply chain network architecture. The PSO algorithms were detailed in the Section 1.

Table 16
Performance evaluation – matrix of outperforming mean TSCC instances of solution methodologies for SCS.

	GA	B-PSO	LDIW-PSO	CFM-PSO	NLIW-PSO
GA	–	0	0	0	0
B-PSO	20	–	0	0	0
LDIW-PSO	20	20	–	0	0
CF-PSO	20	20	20	–	0
NLIW-PSO	20	20	20	20	–

4.2. Particle representation in PSO algorithm for three stage multi-echelon SCN configuration

In proposed PSO algorithm, one solution in a multi-echelon supply chain network configuration is represented by a particle, i.e. one string of integers (decision variables), which is similar to the chromosome in GA. A typical representation of a SCN solution using a swarm particle is shown in the Fig. 2. Number of particles (N) representing the SCN configuration population size called swarm size. Three echelon supply chain network configuration considered in this study is represented by a particle which consists of 30 segments. Details are shown in the Fig. 2a and swarm size $N = 5$ is also represented in Fig. 2b.

4.3. Velocity calculation and position updating equations considered for PSO variants

Following are the equations of PSO variants used for velocity calculation and position updating of particles of PSO.

4.4. Basic particle swarm optimization algorithm equations (B-PSO)

Velocity,

$$v_{kd}^{\text{new}} = \underbrace{v_{kd}}_{\text{Momentum part}} \underbrace{+c_1 \times [r_1 \times (P_{kd} - X_{kd})]}_{\text{Cognitive Part}} \underbrace{+c_2 \times [r_2 \times (G_d - X_{kd})]}_{\text{Social Part}}$$
$$\text{for } d = 1, 2, \ldots, D. \quad (14)$$

$$X_{kd}^{\text{new}} = X_{kd} + v_{kd}^{\text{new}} \quad (15)$$

4.5. Linearly decreasing inertia weight particle swarm optimization algorithm equations (LDIW-PSO)

Velocity:

$$v_{kd}^{\text{new}} = w \times v_{kd} + c_1 \times [r_1 \times (P_{kd} - X_{kd})] + c_2 \times [r_2 \times (G_d - X_{kd})]$$
$$\text{for } d = 1, 2, \ldots, D. \quad (16)$$

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{\text{iter}_{\max}} \times \text{iter} \quad (17)$$

Table 17
Performance evaluation – average iterations and average computational effort of all algorithms.

Scenario	GA		B-PSO		LDIW-PSO		CFM-PSO		NLIWD-PSO	
	Iterations	Time in seconds	Iterations	Time in sec	Iterations	Time in seconds	Iterations	Time in seconds	Iterations	Time in seconds
Average computational effort										
1	1234	134	908	121	232	17	426	95	197	17
2	1324	145	1424	117	240	19	270	21	198	21
3	1242	112	1103	89	198	16	282	21	194	21
4	1232	132	1334	111	205	16	306	23	182	20
5	1063	122	1191	102	210	17	243	19	186	22
6	1122	144	1262	122	264	22	302	23	191	20
7	1543	133	1467	128	214	17	276	17	194	19
8	976	90	892	75	209	17	249	17	191	18
9	1243	111	1111	95	230	18	223	16	208	17
10	1176	87	911	71	202	16	224	16	205	19
11	1287	99	1046	70	206	16	241	17	197	20
12	987	87	889	69	224	18	225	16	195	19
13	1153	121	1017	107	223	18	254	18	197	21
14	1234	87	1130	89	205	16	245	17	212	18
15	1343	87	1238	96	233	19	284	19	205	17
16	876	78	745	61	205	16	215	15	200	20
17	1023	89	754	58	246	19	205	14	193	18
18	986	76	732	57	210	17	236	17	178	17
19	894	65	666	54	199	25	220	15	207	19
20	1124	121	1217	96	229	18	285	20	205	18

Table 18
Decision variables of near global optimal solution (TSCC) of each scenario of SCS by B-PSO algorithm.

Decision variables for optimal (best) solution for each scenario																														
Scenario	X_{111}	X_{112}	X_{121}	X_{122}	X_{131}	X_{132}	X_{211}	X_{212}	X_{221}	X_{222}	X_{231}	X_{232}	X_{311}	X_{312}	X_{321}	X_{322}	X_{331}	X_{332}	Y_{11}	Y_{12}	Y_{13}	Y_{14}	Y_{15}	Y_{16}	Y_{21}	Y_{22}	Y_{23}	Y_{24}	Y_{25}	Y_{26}
1	102	45	133	23	90	109	75	34	235	122	106	17	236	34	62	71	113	126	74	58	35	43	63	44	10	42	21	15	26	46
2	32	114	113	36	153	100	94	53	31	164	199	23	146	90	77	32	80	76	71	45	22	64	54	42	25	18	38	17	39	55
3	80	61	75	100	139	106	78	58	85	81	50	129	61	208	17	93	129	115	19	31	21	42	25	63	69	39	35	41	51	32
4	78	23	137	30	53	150	67	44	95	172	145	71	171	106	69	70	141	27	53	14	58	19	29	79	16	46	38	74	26	3
5	89	84	29	40	146	115	55	40	120	127	95	86	191	57	18	14	74	112	49	56	38	51	19	51	15	23	25	47	39	32
6	99	68	113	117	84	9	61	73	164	90	128	116	100	142	10	83	198	30	49	87	21	62	51	26	14	8	37	27	26	53
7	85	18	173	93	35	111	118	12	43	206	116	120	87	144	46	71	127	55	71	84	1	38	30	36	11	6	91	34	27	46
8	45	68	123	120	69	39	81	33	214	63	40	131	133	204	61	16	21	21	42	17	50	7	39	49	20	57	15	52	59	24
9	78	81	132	51	28	82	75	16	228	148	48	136	210	110	58	52	14	132	27	78	23	27	70	8	47	10	42	52	8	51
10	85	46	73	115	60	78	9	12	85	208	117	3	82	248	30	41	145	88	50	5	40	17	58	34	33	73	30	51	12	24
11	76	65	146	87	73	43	113	5	201	54	27	117	55	236	107	28	167	20	48	33	55	49	34	46	40	26	39	4	28	27
12	34	24	70	123	143	139	24	94	261	78	34	83	199	64	78	20	19	122	62	74	34	14	34	22	34	21	34	38	41	33
13	108	86	20	19	134	131	53	41	162	129	36	118	117	162	79	33	74	53	42	40	39	58	21	47	51	36	34	13	71	26
14	70	31	37	114	106	97	74	74	225	158	40	102	190	114	15	85	66	138	84	10	27	25	42	12	8	56	29	65	37	43
15	24	102	76	144	151	59	20	96	155	39	42	126	106	196	71	33	117	53	68	45	40	6	25	33	13	28	22	80	47	64
16	84	62	67	56	47	152	23	21	128	76	38	154	125	136	28	57	125	28	23	35	18	32	44	35	69	31	47	37	11	23
17	11	76	102	75	96	70	13	128	249	116	2	78	170	128	49	75	124	46	63	31	10	60	18	23	9	54	45	18	39	42
18	126	48	73	68	71	49	78	18	152	130	18	37	222	95	77	61	77	58	23	62	56	35	52	12	38	39	13	24	11	40
19	29	74	107	151	73	14	22	125	74	203	110	51	163	86	21	69	93	45	39	32	34	4	56	40	45	36	25	53	17	19
20	85	45	102	138	27	113	20	10	119	105	57	173	119	148	76	15	19	128	29	35	42	34	32	20	54	47	54	30	49	34

Table 19
Decision variables of near global optimal solution (TSCC) of each scenario of SCS by NLIW-PSO algorithm.

Decision variables for optimal (best) solution for each scenario																														
Scenario	X_{111}	X_{112}	X_{121}	X_{122}	X_{131}	X_{132}	X_{211}	X_{212}	X_{221}	X_{222}	X_{231}	X_{232}	X_{311}	X_{312}	X_{321}	X_{322}	X_{331}	X_{332}	Y_{11}	Y_{12}	Y_{13}	Y_{14}	Y_{15}	Y_{16}	Y_{21}	Y_{22}	Y_{23}	Y_{24}	Y_{25}	Y_{26}
1	137	6	143	48	64	73	107	19	42	81	197	27	155	30	20	95	169	2	59	66	44	47	42	85	24	32	11	10	47	3
2	121	25	96	60	84	100	91	47	161	126	49	12	147	20	105	32	49	133	65	29	37	43	50	77	31	32	23	38	42	19
3	142	35	123	18	49	98	71	5	70	77	173	69	142	56	11	94	161	2	52	37	41	75	52	57	36	33	13	7	24	38
4	175	17	87	35	69	70	69	21	77	36	185	65	142	18	18	108	172	2	48	25	62	80	53	63	20	35	33	13	2	19
5	147	53	73	38	94	41	83	4	35	77	196	51	135	37	3	89	174	10	44	39	30	72	46	80	20	41	33	26	10	2
6	125	75	75	32	98	48	70	17	96	72	134	69	184	64	49	53	66	38	51	46	37	67	49	48	10	49	19	22	26	29
7	149	49	58	28	129	61	72	14	61	73	201	49	134	66	10	100	190	7	49	36	63	66	52	68	33	53	27	5	4	14
8	102	95	42	35	142	13	17	50	112	71	157	23	275	24	8	64	5	71	49	39	26	40	60	72	13	35	37	19	38	1
9	133	67	73	12	90	63	66	18	131	41	100	85	164	23	51	77	82	42	65	45	56	29	63	38	8	41	9	49	15	20
10	116	83	77	29	82	36	62	5	99	81	110	62	170	27	40	61	61	60	56	32	61	32	52	38	25	44	8	34	17	20
11	97	88	108	40	86	10	91	14	96	28	105	92	165	35	32	52	94	56	75	21	64	35	31	63	11	37	29	18	30	9
12	10	101	10	61	235	22	66	28	18	132	170	24	176	53	59	78	19	56	25	61	49	17	63	39	71	34	18	34	11	16
13	181	15	122	41	29	90	67	34	63	61	202	45	148	45	4	96	181	1	61	37	50	58	59	67	30	39	22	11	32	6
14	151	13	112	24	34	98	75	23	32	54	190	58	132	28	16	103	149	2	89	22	22	70	41	53	1	42	32	19	38	1
15	8	127	57	50	219	4	62	50	40	116	182	15	208	94	70	77	12	10	27	65	56	33	25	78	53	7	5	52	46	18
16	95	96	101	5	64	44	4	49	150	66	102	30	218	3	4	43	34	100	50	47	47	52	20	40	41	19	17	17	34	16
17	140	60	55	24	81	47	50	9	124	43	102	82	164	22	43	68	69	43	66	38	52	50	35	35	6	47	1	27	22	28
18	34	102	16	13	215	26	67	40	31	85	164	13	196	44	65	82	7	13	18	65	65	45	41	28	42	35	3	13	21	24
19	136	23	85	13	43	93	60	5	25	59	179	64	108	45	13	82	145	1	65	20	47	35	62	35	17	47	11	21	10	22
20	117	80	63	24	105	66	74	9	131	85	85	76	167	48	38	71	80	52	65	42	88	14	49	27	16	39	7	49	32	27

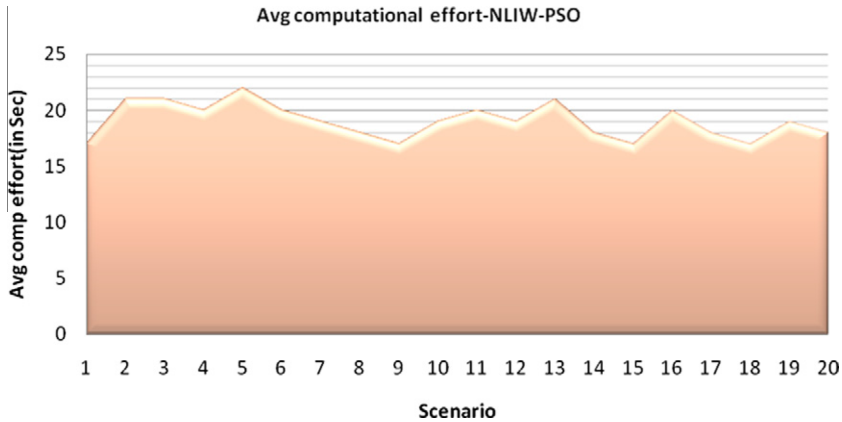

Fig. 5. Performance evaluation – average time (in seconds) took in evaluation of TSCC for each scenario of SCS by NLIW-PSO algorithm.

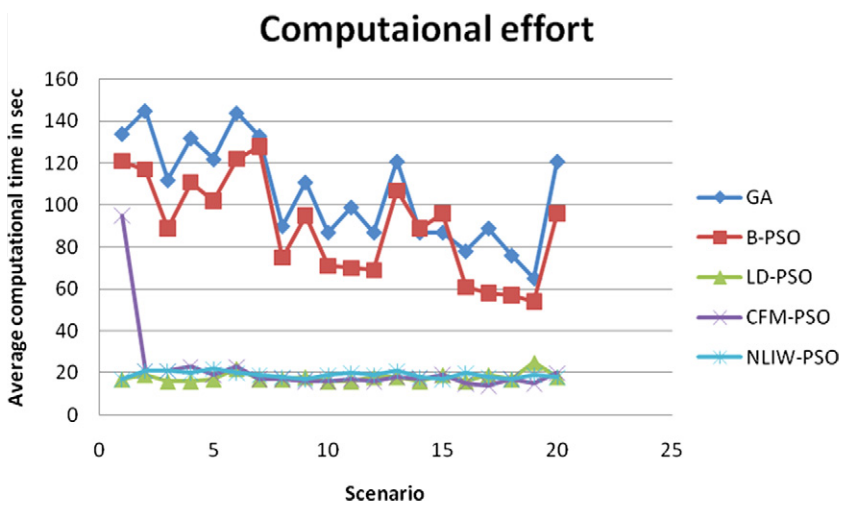

Fig. 6. Performance evaluation – average computational effort in evaluating TSCC for each scenario of SCS-I yielded by heuristics.

Table 20
Statistical analysis of supply chain cost components obtained for best near optimal solutions of each scenario of SCS by NLIW-PSO algorithm.

Scenario	Demand U(50,100)						TMSC	TMSC % of TSCC	TMC	TMC % of TSCC	TDC	TDC % of TSCC	TSCC	Revenue	Profit	TSCC % of revenue	Profit % of revenue
	*R*1	*R*2	*R*3	*R*4	*R*5	*R*6											
1	83	98	55	57	89	90	240250	20.59	908490	77.87	17887	1.53	1166627	1716600	549973	68	32
2	96	61	60	81	92	96	245340	20.29	945600	78.21	18092	1.5	1209032	1786800	577768	68	32
3	88	70	54	82	76	95	236450	20.46	901685	78.01	17654	1.53	1155789	1703400	547611	68	32
4	68	60	95	93	55	82	230270	20.5	875780	77.97	17105	1.52	1123155	1662100	538945	68	32
5	64	79	63	98	56	82	226090	20.54	858150	77.95	16707	1.52	1100947	1620700	519753	68	32
6	61	95	56	89	75	77	230910	20.49	879645	78.04	16650	1.48	1127205	1659100	531895	68	32
7	82	89	90	71	56	82	241365	20.61	911955	77.88	17704	1.51	1171024	1711600	540576	68	32
8	62	74	63	59	98	73	219585	20.55	833465	78	15458	1.45	1068508	1580700	512192	68	32
9	73	86	65	78	78	58	222005	20.42	849470	78.12	15902	1.46	1087377	1605600	518223	68	32
10	81	76	69	66	69	58	214035	20.51	814060	78.02	15270	1.46	1043365	1532800	489435	68	32
11	86	58	93	53	61	72	218670	20.72	820975	77.79	15664	1.48	1055309	1546900	491591	68	32
12	96	95	67	51	74	55	221490	20.28	854525	78.24	16179	1.48	1092194	1594700	502506	68	32
13	91	76	72	69	91	73	242360	20.64	914170	77.85	17849	1.52	1174329	1732300	557971	68	32
14	90	64	54	89	79	54	219430	20.53	833220	77.97	15995	1.5	1068645	1581000	512355	68	32
15	80	72	61	85	71	96	236960	20.43	905520	78.07	17454	1.5	1159934	1703100	543166	68	32
16	91	66	64	69	54	56	204990	20.56	777740	78	14392	1.44	997122	1459500	462378	68	32
17	72	85	53	77	57	63	206800	20.46	789345	78.09	14668	1.45	1010813	1484500	473687	68	32
18	60	100	68	58	62	52	203915	20.48	777270	78.05	14722	1.48	995907	1457200	461293	68	32
19	82	67	58	56	72	57	199225	20.45	760325	78.05	14596	1.5	974146	1435400	461254	68	32
20	81	81	95	63	81	54	230635	20.37	885215	78.18	16482	1.46	1132332	1668200	535868	68	32
Min	60	58	53	51	54	52	199225	20.28	760325	77.79	14392	1.44	974146	1435400	461254	68	32
Max	96	100	95	98	98	96	245340	20.72	945600	78.24	18092	1.53	1209032	1786800	577768	68	32
Average	79.3	77.6	67.8	72	72.3	71.3	224539	20.49	854830	78.02	16321.5	1.49	1095688	1612110	516422	68	32
STD	11.6	13.2	14.2	14	13.6	15.6	13886	0.11	53111	0.12	1221.81	0.03	68119.2	102073	34357.7	0	0

Note: TSC, total supplier cost; TMC, total manufacturing cost; TDC, total distribution cost; TSCC, total supply chain operating cost; STD, standard deviation.

Table 21
Various optimal supply chain cost components of scenario 1 of SCS-I obtained by NLIW-PSO algorithm.

Revenue	TSCC	Profit	TMSC	TMC	TDC
1716600	1166627	549973	240250	908490	17887

Table 22
Optimal procurement of component 1 from vendors for production for scenario 1 of SCS-I obtained by NLIW-PSO algorithm.

	Plant 1	Plant 2
Vendor 1	137	06
Vendor 2	143	48
Vendor 3	64	73

Table 23
Optimal procurement of component 2 from vendors for production for scenario 1 of SCS-I obtained by NLIW-PSO algorithm.

	Plant 1	Plant 2
Vendor 1	107	19
Vendor 2	42	81
Vendor 3	197	27

Table 24
Optimal procurement of component 3 from vendors for production for scenario 1 of SCS-I obtained by NLIW-PSO algorithm.

	Plant 1	Plant 2
Vendor 1	155	30
Vendor 2	20	95
Vendor 3	169	02

Table 25
Optimal product manufacturing and distribution from plants to all distribution centers for scenario 1 of SCS-I obtained by NLIW-PSO algorithm.

	DC 1	DC 2	DC 3	DC4	DC 5	DC 6
Plant 1	59	66	44	47	42	85
Plant 2	24	32	11	10	47	03

where $w_{\max}$ is the initial weight; $w_{\min}$ is the final weight; $\text{iter}_{\max}$ is the maximum iteration number and iter is the current iteration number

$$X_{kd}^{\text{new}} = X_{kd} + v_{kd}^{\text{new}} \tag{18}$$

4.6. Clerc construction factor method particle swarm optimization algorithm equations (CFM-PSO)

Velocity:

$$v_{kd}^{\text{new}} = k' \times (v_{kd} + c_1 \times [r_1 \times (P_{kd} - X_{kd})] + c_2[r_2 \times (G_d - X_{kd})]) \quad \text{for } d = 1, 2, \ldots, D. \tag{19}$$

$$k' = \frac{2}{\left|2 - \phi - \sqrt{\phi^2 - 4\phi}\right|} \tag{20}$$

where $\varphi = c1 + c2$ and $\varphi > 4$.

$$X_{kd}^{\text{new}} = X_{kd} + v_{kd}^{\text{new}} \tag{21}$$

4.7. Nonlinear inertia weight particle swarm optimization algorithm equations (NLIW-PSO)

Velocity,

$$v_{kd}^{\text{new}} = w_{\text{iter}} \times v_{kd} + c_1 \times [r_1 \times (P_{kd} - X_{kd})] + c_2 \times [r_2 \times (G_d - X_{kd})] \tag{22}$$

$$w_{\text{iter}} = \left\{\frac{(\text{iter}_{\max} - \text{iter})^n}{(\text{iter}_{\max})^n}\right\}(w_{\text{initial}} - w_{\text{final}}) + w_{\text{final}} \tag{23}$$

$$m = \frac{(w_{\text{initial}} - w_{\text{final}})}{\text{iter}_{\max}} \tag{24}$$

$$w_{\text{final}} = w_{\text{initial}} + m \times \text{iter}_{\max} \tag{25}$$

$$X_{kd}^{\text{new}} = X_{kd} + v_{kd}^{\text{new}} \tag{26}$$

4.8. General structure of Optimization of three stage multi-echelon supply chain network architecture Using PSO algorithm

Following are the general procedural steps involved in the optimization of three stage multi echelon supply chain network architecture using PSO algorithm (see Fig. 3).

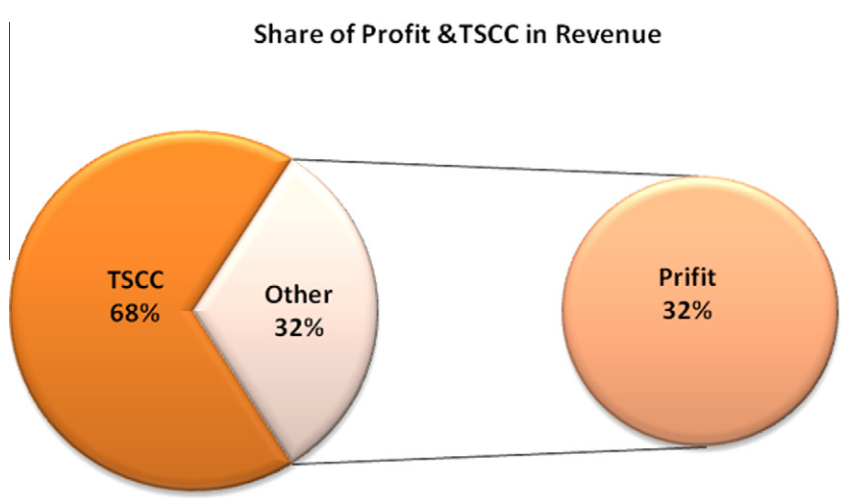

Fig. 7. Share of TSCC and profit in total revenue generated for scenario 1 of SCS by NLIW-PSO algorithm.

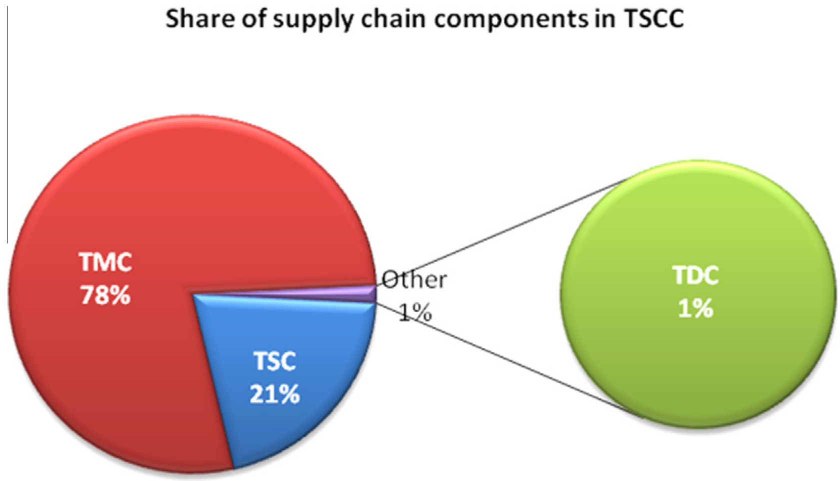

Fig. 8. Share of TSC, TMC AND TDC in TSCC for scenario 1 of SCS by NLIW-PSO algorithm.

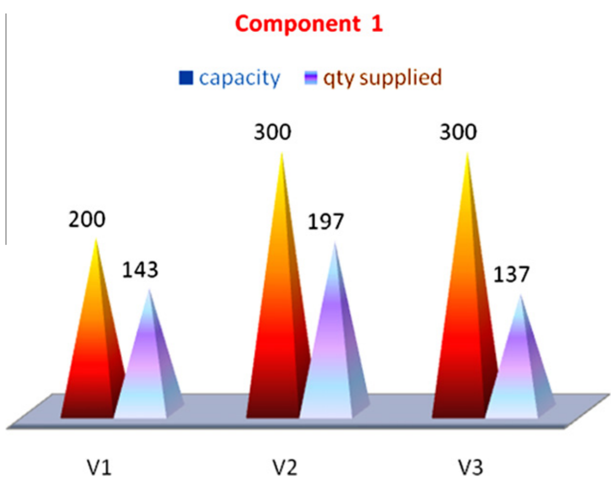

Fig. 9. Optimal procurement of component 1 from vendors for production vs capacity of vendors for scenario 1 of SCS obtained by NLIW-PSO algorithm.

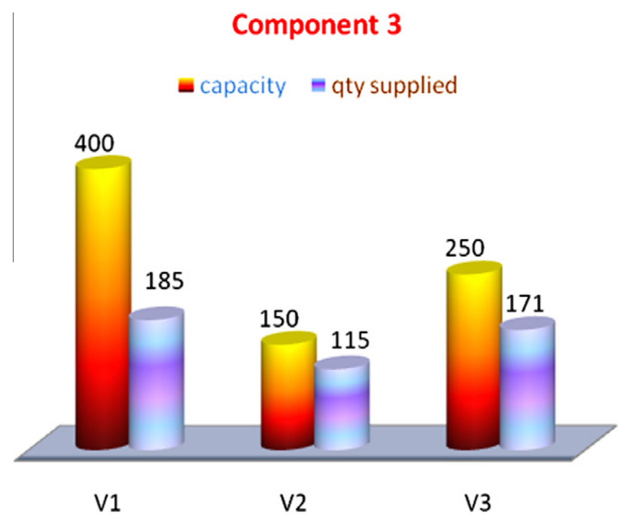

Fig. 11. Optimal procurement of component 3 from vendors for production vs capacity of vendors for scenario 1 of SCS obtained by NLIW-PSO algorithm.

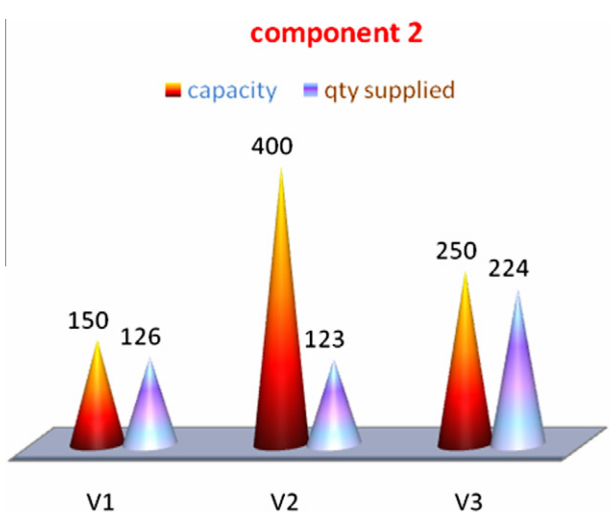

Fig. 10. Optimal procurement of component 2 from vendors for production vs capacity of vendors for scenario 1 of SCS obtained by NLIW-PSO algorithm.

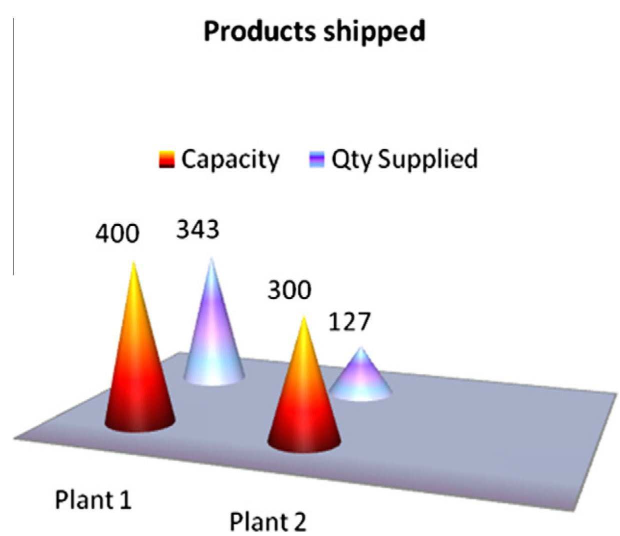

Fig. 12. Optimal manufacture of goods from plants vs their capacity for scenario 1 of SCS obtained by NLIW-PSO algorithm.

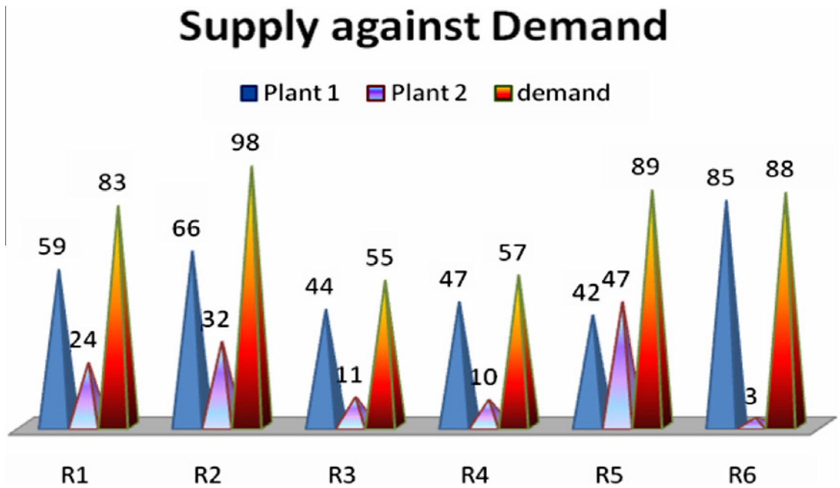

Fig. 13. Optimal supply of goods from plants to retailers against demand for scenario 1 of SCS obtained by NLIW-PSO algorithm.

5. Input data for the supply chain model

This sub section illustrates the input data related to vendors, manufactures and distribution centers for the analysis of three echelon supply chain network.

The input data of the SCS are exhibited in the Tables 1–8. The data information of all the vendors about their capacities for each component, the cost of components, and the transportation costs for all the components are represented in Tables 1–5 for SCS. The manufacturing plant capacity, labor cost of manufacturing a product, manufacturing cost of product and inventory carrying cost of each plant for SCS is shown in Table 6. Plant transportation cost of product to all dealers and Selling price of product at different dealers are listed in Tables 7 and 8 for SCS.

6. Results and discussions

This subsection discusses and summarizes the results of the test problem considered in this study. The performances of the PSO algorithms were evaluated by considering the supply chain test problem, supply chain setting. Twenty demand scenarios are considered in this study to evaluate the performance of the proposed PSO variants. For all the 20 scenarios demand rates are generated using the uniform distribution with a minimum demand of 50 units and a maximum demand of 100 units for SCS. Same demand settings are considered to comparatively evaluate the performances of the PSO algorithms considered in this study. The performances of the heuristic methodologies are analyzed by the quality of the solutions yielded and computational effort required to obtain the best solution. To test the solution quality, statistical analysis has been carried out to find whether there exists any significant difference between the mean TSCC values yielded by different solution methodologies of PSO variants (i.e. B-PSO, LDIW-PSO, CFM-PSO and NLIW-PSO).

For fair comparison, the proposed PSO algorithms were tested on the same computer platform by fixing the same number of iterations. TSCC obtained, after running the PSO variants to a maximum number of iterations are reported in Tables 9–12. The table also gives the mean, best, worst, and standard deviation value of TSCC over 15 replications for each scenario.

The result of statistical analysis shows that there exists a significant difference between solution obtained by B-PSO and the solutions yielded by different solution methodologies for supply chain setting test problems. All other heuristic methodologies yielded solutions, which are not so significantly different from each other. To evaluate best performing algorithm for the SCS, the mean relative percentage error or increase in the objective function value is evaluated.

To evaluate the best performing algorithm, the best and mean relative percentage increase in TSCC are calculated by using above equation and the data are tabulated in Table 13 and in Table 15 and pictorially shown in Fig. 4. It is seen from the outperformed matrix Table 14 for best value of TSCC and Table 16 for mean value of TSCC, that for most of problem instances, Non linear inertia weight approach (NLIW-PSO) perform very well and produces better quality solutions when compared with other variants of PSO and GA.

An another important key determinant of measure of effectiveness to evaluate the performance of the solution procedure is the computational effort required by an algorithm, which is expressed in terms of the number of iterations and time in seconds that an algorithm has enumerated to converge to the near optimal solutions of TSCC. This computational effort for each seed in obtaining feasible solution (TSCC) for all scenarios for various solution methodologies of PSO tabulated. The average Computational effort involved in obtaining feasible solution (TSCC) for all scenarios for various solution methodologies of PSO and their relative performance analysis are evaluated and compared in Table 17 and the results are shown in Fig. 6. It is evident from figure that, LDIW-PSO, CFM-PSO and NLIW-PSO took very less computational time in evaluation of feasible solutions in comparison with B-PSO and GA, i.e. the these algorithms gave fairly good solutions with the reasonable computational effort. Whereas NLIW-PSO took very computational time in evaluation of feasible solutions in comparison with all PSO variants and GA and also it outperformed and produced better quality solutions in comparison with all solution methodologies used in this research work. The better results are due to the novel solution construction procedure implemented to generate a new particle on the basis of non linear inertia weight variation of dynamic adaptation in PSO algorithm. The average computational effort taken by each scenario for NLIW-PSO is graphically represented in Fig. 5.

Decision variables for the best TSCC obtained by B-PSO and NLIW-PSO for the SCN considered in this work are exhibited in Tables 18 and 19 respectively. The cost components, revenue and profit for the best solution of TSCC of all the scenarios of best performing algorithm NLIW-PSO are shown in Table 20.

A sample of near best optimal supply chain cost components, optimal procurement of component 1, component 2, component 3 from vendor 1, vendor 2, vendor 3, and optimal product manufacturing and distribution from plant1 and plant 2 to all six distribution centers to satisfy the demand, obtained by best solution algorithm NLIW-PSO for scenario 1of SCS is listed in Tables 21–25, respectively. The share of TSCC and profit in revenue and share of TSC, TMC and TDC in TSCC are shown in Figs. 7 and 8, respectively. Figs. 9–11 shows optimal procurements of components from vendors for production against the capacity of vendors. Fig. 12 depicts the optimal manufacture of products from each plant against their capacity. Optimal distribution of products from plants to all distribution centers against demand is shown in Fig. 13.

7. Conclusions

The present work in this chapter considered the mathematical modeling of three echelon supply chain network and application of variants of particle swarm optimization algorithm for the best alignment of procurement, production and distribution in three echelon supply chain network in order to optimize TSCC in supply chain network optimization for the first time.

Four particle swarm optimization algorithms are proposed for the application to solve three echelons SCN architecture and the results were compared with Genetic algorithm. The first algorithm called B-PSO is a basic PSO algorithm, where no inertia weight is considered for the velocity updating of particle. The second algorithm LDIW-PSO called linearly decreasing inertia weight PSO algorithm, where linearly decreasing inertia weight is used to update the particle velocity. The third algorithm CFM-PSO called construction factor method, where the fixed inertia weight is used to update the velocity of the particle. The fourth algorithm called non linear inertia weight (NLIW-PSO) PSO, where particle velocity is updated dynamically updating. Extensive performance analysis using the PSO variants have been carried out on real word SCN problems. Results indicates, Non-linear inertia weight PSO algorithm (NLIW-PSO) generating better quality solutions to the problem considered in this study. The better performance of the above solution methodology is due to the novel solution construction procedure implemented in the algorithm.

Acknowledgements

The authors would like to thank the anonymous referees and the editor for their constructive comments on the earlier version of the paper.

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