Optimizing bi-objective, multi-echelon supply chain model using particle swarm intelligence algorithm

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Abstract. In the current globalized scenario, business organizations are more dependent on cost effective supply chain to enhance profitability and better handle competition. Demand uncertainty is an important factor in success or failure of a supply chain. An efficient supply chain limits the stock held at all echelons to the extent of avoiding a stock-out situation. In this paper, a three echelon supply chain model consisting of supplier, manufacturing plant and market is developed and the same is optimized using particle swarm intelligence algorithm.

1. Introduction
Current technology has turned the world into a global village. Business organizations (BO) world over are striving to improve their market share, increase revenue and profit with the core objective of customer satisfaction drifted to customer delight. Most BO concentrate on product / services warranting their core competency, and outsource other products to similar such BOs, which ensures high quality at low cost and more importantly the scope to improve continuously in both function of product or component and processes in making the product or component. BO world over are thus opting to rely more on its supply chain (SC) for their daily production, which has evolved due to advances in communication and transportation technologies[1][4][5].

SC strategy is vital for success of any business organization; it ought to be viewed as a living entity. Clearly defined SC objective(s) should drive the SC strategy, which in turn should drive the tactics of SC; ensuring all departments of a business organization to align their individual goals to that of the organizations. Total operation cost (TOC) and time are most often used performance metrics in evaluating a supply chain model (SCM). TOC is the aggregation of cost of material, components, labour, machine time both utilized and idle, inventory carrying cost, lost sales, transportation cost, and the like. Cost reduction in any constituent of the TOC, and a continuous improvement initiative would reduce further due to this. Apart from cost minimization, an efficient SC enjoys low inventory level maintained across all its echelons. Such low inventory levels reduce costs by surfacing any problems at early stages and improve in understanding and better serving the dynamically changing needs and demands of customer. Members of the SC ought to be more responsible and reliable in satisfying the needs and demands of members in downstream echelon, warranting a well-established and robust information sharing system both intra and inter echelon. Just-in-time

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production system adopted by many companies is a noteworthy example for existence of reliable SC which helped reduce the inventory carrying cost (IC) [2][3][8][13]. Industry continuously strives to determine the right resource usage for optimized cost computation. Researchers employ different evolutionary algorithms that mimic natural processes to optimize resources. Particle swarm intelligence optimization (PSO) is an evolutionary algorithm developed by Eberhart and Kennedy (1995) that mimics the behaviour of swarm of birds or school of fish. Kadadevaramath et al. (2012) developed a three echelon SCM and used PSO to optimize the resource usage [6]. PSO is very robust in exploring and exploiting the search space of multi echelon SC problems that usually have many decision variables and are multi-objective in nature[7][9]. PSO relies both on its own cognitive behaviour and shared social behaviour of swarm or school to initially locate local optima and gradually move towards global optimal[10][11][12].

2. Problem definition and formulation of multi-objective mathematical model

2.1 Model description
A three echelon supply chain model is developed with five suppliers in the third echelon, three manufacturing plant in the second echelon and four market area in the first echelon as shown the fig. 1.

![Figure 1. Three echelon Supply Chain Model](image)

Three components are supplied by five suppliers to three plants, which manufacture the finished product that is sold in the four market area. Total operating cost (TOC) is the key metric in evaluating the performance of the supply chain. TOC is the aggregation of total manufacturing cost (TMC), inventory cost (IC) and transportation cost (TC). TMC is the cost incurred by both the supplier and manufacturing plant in manufacturing the finished product. IC is the inventory carrying cost of excess components or finished products remaining at the end of a particular time period at manufacturing plant and market area. TC includes the cost of transporting components from supplier to manufacturing plant and the finished product from plant to market area.

2.2 Model Assumption
- Supplier facility operating at full capacity
- All finished product is sent to market at the end of each time period
End product is made of three components.

Fixed costs of all the vendor facilities are constant and same; it is not included in cost calculation.

No backorder is allowed.

Quantity of goods is always expressed as integer.

Demand at market varies randomly.

Excess inventory at the end of each time period in all the three echelons are considered for inventory carrying cost computation.

2.3 Objective

To determine the optimum TOC by converging the deviational variables of the ratios TC/TOC and IC/TOC to respective predetermined targets, using PSO.

2.4 Mathematical model formulation

A multi-objective of a three echelon SCM is presented by incorporating the goals and respective deviational variables:

- \( L_{c,s} \) Capacity of supplier 's' for component 'c'
- \( CS_{c,s} \) Cost of making component 'c' by supplier 's'
- \( STC_{c,s,p} \) Unit transportation cost of component 'c' from supplier 's' to plant 'p'
- \( U_p \) Capacity of plant 'p'
- \( MC_p \) Unit manufacturing cost at plant 'p'
- \( IC_{c,p} \) Inventory carrying cost of component 'c' at plant 'p' (per unit)
- \( IC_{f,p} \) Inventory carrying cost of finished product at plant 'p' (per unit)
- \( PTC_{p,m} \) Transportation cost from plant 'p' to market 'm'
- \( B_{c,s,p} \) Boolean variable for transporting component 'c' by supplier 's' to plant 'p'
- \( B_{p,m} \) Boolean variable for transporting finished product from plant 'p' to market area
- \( D_m \) Demand in market 'm'
- \( SP_m \) Selling price at market 'm'
- \( X_{c,s,p} \) Quantity of component 'c' supplied by supplier 's' to plant 'p'
- \( Y_{p,m} \) Quantity of finished product supplied from plant 'p' to market 'm'
- \( TR_{TMC} \) Target ratio TMC
- \( TR_{IC} \) Target ratio of IC
- \( TR_{TC} \) Target ratio of TC
- \( \theta^*_i, \theta^*_j \) Deviational variables of the ratio TC/TOC
- \( \theta^*_i, \theta^*_j \) Deviational variables TOC
\[
TMC = \sum_{c} \sum_{s} \sum_{p} (X_{c,s,p} \cdot CS_{c,s}) + \sum_{p} \sum_{m} (Y_{p,m} \cdot MC_{p}) \tag{1}
\]

\[
IC = \sum_{c} \sum_{p} (IC_{c,p} \left( \frac{X_{c,s,p}}{n} - Y_{p,m} \right) + \sum_{p} (IC_{p,m} \cdot (Y_{p,m} - D_{m}) \tag{2}
\]

\[
TC = \sum_{c} \sum_{s} \sum_{p} (X_{c,s,p} \cdot STC_{c,s,p} \cdot B_{c,s,p}) + \sum_{p} \sum_{m} (Y_{p,m} \cdot PTC_{p,m} \cdot B_{p,m}) \tag{3}
\]

\[
TOC = TC + TMC + IC \tag{4}
\]

\[
\sum_{m} Y_{p,m} \leq U_{p} \quad \forall \ p \tag{5}
\]

\[
\sum_{p} X_{c,s,p} \leq L_{c,s} \quad \forall \ c, s \tag{6}
\]

\[
\sum_{s} X_{c,s,p} - \sum_{m} Y_{p,m} \geq 0 \quad \forall \ c, p \tag{7}
\]

\[
\frac{IC}{TOC} + \theta_i^- - \theta_i^+ \leq TR_{IC} \tag{8}
\]

\[
\frac{TC}{TOC} + \theta_j^- - \theta_j^+ \leq TR_{TC} \tag{9}
\]

\[
\text{Minimize } Z_1 = \theta_i^+ + \theta_j^- \tag{10}
\]

Equations (1) to (4) depict the computation of TMC, IC, TC and TOC. System constraint equations (5) and (6) ensure that plant and supplier operate within their respective rated capacities. Equation (7) is an inventory balancing constraint in the plants. Goal constraints (8) and (9) strive to optimize the individual cost ratios and hold the deviations in the respective deviational variables. Objective function depicted in equation (10) converges the deviational variables of the ratios TC/TOC and IC/TOC to the predetermined values.

3 Optimization of multi-objective three stage multi-echelon supply chain architecture using PSO algorithms

3.1 Introduction to PSO Algorithm

Velocity of a particle’s dimension is computed in an iteration using equations – to –

\[
v_{n+1} = \omega v_n + C_1 [r_1 (P_{best} - X_n)] + C_2 [r_2 (G_{best} - X_n)] \tag{11}
\]

\[
\omega = \text{Rand}(0, 1) \tag{12}
\]
\[ X_{n+1} = X_n + v_{n+1} \]  \hspace{1cm} (13)

First part of the equation (13) is the inertia of the dimension of a particle, second part is cognitive part that influences its own best positions in previous iterations, and the last is the social influence of best position held by a member of the swarm.

### 3.2 Particle representation in PSO

Decision variable \( X_{c,r,p} \) refers to the quantity of component 'c' supplied by supplier 's' to plant 'p' and \( Y_{p,m} \) refers to the quantity of finished product supplied from plant 'p' to market 'm' [6]. Fig. 2 depicts the representation of one particle consisting of 57 dimensions and the swarm size is twenty particles.

![Particle representation of a three echelon SCM in PSO algorithm](image)

Figure 2. Particle representation of a three echelon SCM in PSO algorithm

### 3.3 Velocity calculation and new position updating in PSO

Inertia weight for velocity computation of a dimension of a particle in the swarm helps convergence towards solution. In the initial iterations, cognitive part and the social part would not have explored the search space, hence weightage to these would be maintained at lower levels and inertia weight is assigned higher weight so as help explore the solution space. But at higher iterations, inertia weight ought to be controlled, so that the algorithm converges towards solution, whereas cognitive part and social part are assigned higher weightage.

#### 3.3.1 Basic particle swarm optimization algorithm equations (B – PSO)

\[ v_{n+1} = v_n + C_1 [r_1 (P_{best} - X_n)] + C_2 [r_2 (G_{best} - X_n)] \]  \hspace{1cm} (14)

\[ X_{n+1} = X_n + v_{n+1} \]  \hspace{1cm} (15)

#### 3.3.2 Linearly decreasing inertia weight particle swarm optimization algorithm equations (LDIW-PSO)

\[ v_{n+1} = \omega v_n + C_1 [r_1 (P_{best} - X_n)] + C_2 [r_2 (G_{best} - X_n)] \]  \hspace{1cm} (16)

\[ \omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{iter_{max}} \cdot iter \]  \hspace{1cm} (17)

\[ X_{n+1} = X_n + v_{n+1} \]  \hspace{1cm} (18)

#### 3.3.3 Global – local best inertia weight particle swarm optimization algorithm equations (GLBIW-PSO)

\[ v_{n+1} = \omega v_n + C_1 [r_1 (P_{best} - X_n)] + C_2 [r_2 (G_{best} - X_n)] \]  \hspace{1cm} (19)
\[ \omega = (1.1 - \frac{G_{best}}{P_{best}}) \]  
\[ X_{n+1} = X_n + v_{n+1} \]  

4 Results and discussions

The SCM developed is optimized using PSO algorithm with inertia weight computed by B-PSO, LDIW and GLBIW. Twenty demand scenarios were developed using uniform distribution with a maximum demand of 100 units and a minimum of 50 units and the same is used for all three methods computing the inertia weight. Performance of the PSO algorithms are analysed based on the quality of the solution and the computational effort. Each demand scenarios was replicated ten times for each method of the inertia weight computation and the best TOC, worst TOC, mean of the ten replicated TOC and its standard deviation is tabulated in the table 1. It is observed that for all the demand scenarios best TOC and mean of TOC computed using GLBIW-PSO is lower than computed using B-PSO and LDIW-PSO.

![Figure 3. Average computational effort to computing TOC using PSO](image)

![Figure 4. Average computational time to computing TOC using PSO](image)
| D.S   | TOC based on $B$ – PSO equations | TOC based on LDIW – PSO equations | TOC based on GLBIW – PSO equations |
|-------|---------------------------------|-----------------------------------|-----------------------------------|
|       | Best   | Worst   | Mean   | Std. Dev. | Best   | Worst   | Mean   | Std. Dev. | Best   | Worst   | Mean   | Std. Dev. |
| 1     | 1240429 | 1334287 | 1286577 | 30892     | 1182463 | 1279413 | 1232213 | 30239     | 1172061 | 1203340 | 1190910 | 10733     |
| 2     | 1269462 | 1350846 | 1313752 | 25869     | 1222504 | 1342004 | 1281721 | 32659     | 1209890 | 1234036 | 1222689 | 7474      |
| 3     | 1238299 | 1312278 | 1273760 | 24173     | 1168645 | 1278265 | 1226178 | 38013     | 1162189 | 1197808 | 1175957 | 12288     |
| 4     | 1193743 | 1282279 | 1234066 | 34324     | 1182231 | 1244898 | 1218590 | 25054     | 1125460 | 1195321 | 1163860 | 20062     |
| 5     | 1196645 | 1272618 | 1241508 | 22362     | 1105636 | 1234726 | 1177238 | 42982     | 1102820 | 1132682 | 1120551 | 9953      |
| 6     | 1209190 | 1322878 | 1262080 | 40247     | 1141503 | 1249743 | 1192646 | 31716     | 1127288 | 1152134 | 1142896 | 6568      |
| 7     | 1241759 | 1300558 | 1275295 | 17694     | 1204205 | 1277535 | 1242780 | 26597     | 1173345 | 1206333 | 1190916 | 10894     |
| 8     | 1124444 | 1266702 | 1193029 | 34761     | 1080101 | 1173226 | 1111834 | 30016     | 1069674 | 1096267 | 1082828 | 9606      |
| 9     | 1172374 | 1217478 | 1226884 | 31288     | 1121737 | 1295820 | 1207927 | 53198     | 1091983 | 1132400 | 1114593 | 12403     |
| 10    | 1119556 | 1190388 | 1157877 | 22444     | 1063668 | 1196127 | 1141185 | 44267     | 1044506 | 1076925 | 1060282 | 11167     |
| 11    | 1139321 | 1238320 | 1178445 | 26170     | 1092472 | 1195146 | 1146958 | 37451     | 1056810 | 1084939 | 1071380 | 8104      |
| 12    | 1171557 | 1236193 | 1206302 | 20860     | 1110591 | 1196874 | 1150670 | 30853     | 1093475 | 1109406 | 1102521 | 5830      |
| 13    | 1231343 | 1356967 | 1289079 | 35791     | 1199696 | 1330639 | 1273846 | 45630     | 1175640 | 1189033 | 1182827 | 4605      |
| 14    | 1177902 | 1253093 | 1226586 | 23086     | 1062401 | 1183279 | 1140907 | 44267     | 1072400 | 1129531 | 1101624 | 21146     |
| 15    | 1232478 | 1304515 | 1268107 | 24071     | 1174907 | 1280336 | 1237714 | 33757     | 1162629 | 1185994 | 1174031 | 7684      |
| 16    | 1066813 | 1188655 | 1122548 | 41845     | 1000760 | 1129027 | 1062771 | 43310     | 998505 | 1033318 | 1013546 | 11852     |
| 17    | 1103923 | 1179008 | 1140408 | 24518     | 1042108 | 1175237 | 1100826 | 49821     | 1017244 | 1033638 | 1025381 | 5795      |
| 18    | 1055007 | 1191381 | 1130840 | 42573     | 1014553 | 1139280 | 1078537 | 45173     | 996124 | 1022321 | 1008041 | 9290      |
| 19    | 1070786 | 1155096 | 1109526 | 23205     | 989025 | 1161841 | 1057411 | 58418     | 977691 | 1018080 | 996111 | 13271     |
| 20    | 1192632 | 1288115 | 1236017 | 26484     | 1150048 | 1250886 | 1203847 | 30340     | 1133873 | 1161331 | 1145607 | 8116      |
### Table 2. Performance evaluative of three echelon SCN yielded by three variants of PSO

| DS | Performance evaluation based on mean of TOC | Performance evaluation based on best of TOC |
|----|---------------------------------------------|---------------------------------------------|
|    | B-PSO | LDIW | GLBIW | B-PSO | LDIW | GLBIW | B-PSO | LDIW | GLBIW | B-PSO | LDIW | GLBIW |
|    | relative percentage increase | relative percentage increase | relative percentage increase | relative percentage increase | relative percentage increase | relative percentage increase | relative percentage increase | relative percentage increase | relative percentage increase | relative percentage increase | relative percentage increase | relative percentage increase |
| 1  | 1240429 | 1182463 | 1172061 | 5.83 | 0.89 | 0 | 1286577 | 1232213 | 1190910 | 8.03 | 3.47 | 0 |
| 2  | 1269462 | 1222504 | 1209890 | 4.92 | 1.04 | 0 | 1313752 | 1281721 | 1222689 | 7.45 | 4.83 | 0 |
| 3  | 1238239 | 1168645 | 1162189 | 6.54 | 0.56 | 0 | 1273760 | 1226178 | 1175957 | 8.32 | 4.27 | 0 |
| 4  | 1193743 | 1182231 | 1125460 | 6.07 | 5.04 | 0 | 1234066 | 1218590 | 1163860 | 6.03 | 4.70 | 0 |
| 5  | 1196645 | 1105636 | 1102820 | 8.51 | 0.26 | 0 | 1241508 | 1177238 | 1120551 | 10.79 | 5.06 | 0 |
| 6  | 1209190 | 1141503 | 1127288 | 7.27 | 1.26 | 0 | 1262080 | 1192646 | 1142896 | 10.43 | 4.35 | 0 |
| 7  | 1241759 | 1204205 | 1173345 | 5.83 | 2.63 | 0 | 1275295 | 12242780 | 1190916 | 7.09 | 4.35 | 0 |
| 8  | 1124444 | 1080101 | 1069674 | 5.12 | 0.97 | 0 | 1193029 | 1111834 | 1082828 | 10.18 | 2.68 | 0 |
| 9  | 1195238 | 1121737 | 1091983 | 7.36 | 2.72 | 0 | 1226884 | 1207927 | 114593 | 10.07 | 8.37 | 0 |
| 10 | 1119556 | 1063668 | 1044506 | 7.19 | 1.83 | 0 | 1157877 | 1114185 | 1060282 | 9.20 | 5.08 | 0 |
| 11 | 1139321 | 1092472 | 1056810 | 7.81 | 3.37 | 0 | 1178445 | 1146958 | 1071380 | 9.99 | 7.05 | 0 |
| 12 | 1171575 | 1110591 | 1093475 | 7.14 | 1.57 | 0 | 1206302 | 1150670 | 1102521 | 9.41 | 4.37 | 0 |
| 13 | 1231343 | 1196969 | 1175640 | 4.74 | 2.05 | 0 | 1289079 | 1273846 | 1182827 | 8.98 | 7.70 | 0 |
| 14 | 1177902 | 1062401 | 1072400 | 10.87 | 0.93 | 0 | 1226586 | 1140907 | 1101624 | 11.34 | 3.57 | 0 |
| 15 | 1232478 | 1174907 | 1162629 | 6.01 | 1.06 | 0 | 1268107 | 1237714 | 1174031 | 8.01 | 5.42 | 0 |
| 16 | 1068813 | 1000760 | 998505 | 6.84 | 0.23 | 0 | 1125248 | 1062771 | 1013546 | 10.75 | 4.86 | 0 |
| 17 | 1103923 | 1042108 | 1017244 | 8.52 | 2.44 | 0 | 1140408 | 1100826 | 1025381 | 11.22 | 7.36 | 0 |
| 18 | 1055007 | 1014553 | 996124 | 5.91 | 1.85 | 0 | 1130840 | 1078537 | 1000840 | 12.18 | 6.99 | 0 |
| 19 | 1070786 | 989025 | 977691 | 9.52 | 1.16 | 0 | 1109526 | 1057411 | 996111 | 11.39 | 6.15 | 0 |
| 20 | 1192632 | 1150048 | 1133837 | 5.19 | 1.43 | 0 | 1236017 | 1203847 | 1145607 | 7.89 | 5.08 | 0 |

### Table 3. Matrix of performing variant of PSO based on best TOC

| B-PSO | LDIW | GLBIW |
|-------|------|-------|
| 20    | 19   | 20    |
| 19    | 20   | 19    |

### Table 4. Matrix of performing variant of PSO based on mean TOC

| B-PSO | LDIW | GLBIW |
|-------|------|-------|
| 20    | 19   | 20    |
| 19    | 20   | 19    |


Table 5. Ratios of IC/TOC and TC/TOC for best case scenario using GLBIW - PSO

| Demand Scenarios | Demand in market area | IC | IC as % of TOC | TMC | TMC as % of TOC | TC | TC as % of TOC |
|------------------|----------------------|----|---------------|-----|----------------|----|--------------|
| C1               | 90                   | 88 | 95            | 77  | 171121         | 14.6| 639008       |
| C2               | 92                   | 73 | 70            | 97  | 183661         | 15.18| 622246       |
| C3               | 72                   | 59 | 82            | 82  | 184091         | 15.84| 613055       |
| C4               | 90                   | 79 | 87            | 98  | 164205         | 14.59| 594693       |
| C5               | 68                   | 99 | 67            | 54  | 173915         | 15.77| 569827       |
| C6               | 69                   | 55 | 66            | 73  | 161991         | 14.37| 617979       |
| C7               | 80                   | 94 | 62            | 87  | 171778         | 14.64| 633841       |
| C8               | 75                   | 58 | 98            | 81  | 169329         | 15.83| 559974       |
| C9               | 61                   | 84 | 84            | 91  | 173516         | 15.89| 568268       |
| C10              | 59                   | 65 | 83            | 60  | 159809         | 15.3 | 535414      |
| C11              | 96                   | 82 | 60            | 75  | 153554         | 14.53| 551866       |
| C12              | 89                   | 72 | 67            | 69  | 159866         | 14.62| 597584       |
| C13              | 86                   | 71 | 63            | 93  | 178345         | 15.17| 642840       |
| C14              | 98                   | 87 | 95            | 65  | 151852         | 14.16| 559257       |
| C15              | 87                   | 67 | 64            | 98  | 180091         | 15.49| 605265       |
| C16              | 63                   | 56 | 95            | 70  | 142287         | 14.25| 545184       |
| C17              | 53                   | 89 | 55            | 99  | 160318         | 15.76| 537410       |
| C18              | 61                   | 80 | 75            | 77  | 156690         | 15.73| 510215       |
| C19              | 91                   | 70 | 72            | 59  | 153106         | 15.66| 520034       |
| C20              | 74                   | 69 | 68            | 95  | 165313         | 14.58| 593450       |

Best performing algorithm is evaluated based on the best and mean relative percentage increase of TOC using the three inertia weight computation procedures and is tabulated in table 2. Outperformed matrix for best value of TOC is depicted in table 3 and that of mean value of TOC is in table 4. It could be observed that GLBIW – PSO algorithm provides high quality solutions when compared to B-PSO and LDIW-PSO and solutions. Besides high quality of solution, computational effort is an important factor in evaluating the performance of solution procedure. Computational effort involves selection of initial random feasible solutions which are iterated to converge to the global optima. Fig. 3 depicts the average number of iterations for the PSO algorithm to converge to solution using all three inertia weight computing procedures and corresponding time taken is depicted in Fig. 4.
Ratios of IC/TOC, TC/TOC and all other cost components of the best instance of GLBIW-PSO is depicted in table 5, it could be further observed that the ratios of IC/TOC and TC/TOC is well within the predetermined value and are consistent for all the demand scenarios.

5. Conclusions
A three-echelon SCM was developed with five suppliers supplying three components to three manufacturing plants to produce one finished product and sold in four market area. A multi-objective mathematical model was developed, which handles the deviational variables that hinders achieving predetermined target for IC/TOC and ratio of TC/TOC. The model was optimized using PSO algorithm; with the inertia weight computed using B-PSO, LDIW–PSO and GLBIW-PSO. B-PSO has no inertia weight in velocity computation. LDIW-PSO decreases the inertia weight in updating velocity of particles linearly with respect to the number of iterations, whereas GLBIW-PSO updates the velocity of particles based on the individual particles best position and global best position of all particles. Results indicate, GLBIW-PSO generates least TOC solutions to the problem considered with least computational effort.

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