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New Strategy to Optimize Lean Supply Chain Design by Meta-Heuristic

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Abstract: This paper aims at presenting one novel quantitative strategy of optimizing the design of Lean supply chain using Meta-Heuristics. While classifying Lean Manufacturing tools in two categories, namely Functional and Tier Lean tools, we propose a new framework to design the Lean supply chain by implementing the former into a 5-echelon Fat supply chain. As the following step, we investigate the effect of the latter on the mentioned Lean supply chain model. Then, we utilize the tight correlation of Tier Lean tools and priority-based Genetic Algorithm Meta-Heuristics in order to optimize the configuration of the Lean supply chain. Finally, these ideas are illustrated step by step in one numeral example.

Keywords: Lean Supply Chain Design, Functional Lean Tools, Tier Lean Tools, Priority-Based Genetic Algorithm, Optimization

Introduction

Supply Chain Management (SCM) is a respected area today, as future competition in the field of business will be based on Supply Chains (SC) system rather than individual enterprises (Rice and Hoppe, 2001). Several models of SC have been studied as part of the incessant efforts taken to improve the competitive advantages of enterprises. Among them, the Lean Supply Chain (LSC) is assessed as an "ideal SC" (Srinivasan, 2012) since it can promptly and economically deliver the final products/services to customers in a seamless manner. The objective of the LSC is to eliminate non-value added activities as well as reduce the required non-value added activities (Anand and Kodali, 2008). Deborah (2005) analyses and compares the characteristics of the Fat Supply Chain (FSC) and LSC, thereby asserting the undeniable benefits and power of the LSC over the FSC.

In the SCM domain, the Supply Chain Design (SCD) directly impacts the performance of the SC since it creates a proper platform for all activities in the chain. Harrison (2001) suggests that approximately 80% of the total product cost may be fixed with SCD decisions. Nonetheless, the design space of the SCD contains a vast number of alternatives (Leukel and Sugumaran, 2013), which makes it hard to define the best solutions. Over time, the developments of information technology and optimization techniques make this difficulty solvable through optimization, simulation, or heuristics (Harrison, 2001). Recently, numerous Meta-Heuristics (MH) which are improved from heuristics, have proven effective in resolving SCD issues.

Inspired by such attractions, we introduce in this study a new quantitative strategy to design LSC by MH. The forthcoming sections in this study are organized into as followings: Literature review; new strategic framework of the Lean Supply Chain Design (LSCD), including the FSC formation, LSC transformation and its optimization by priority-based Genetic Algorithm (pGA); a numerical example; and conclusion.

Literature Review

SCD is a rich domain of SCM. Farahani *et al.* (2015) classifies SCD into five main rubrics: (1) Network structure; (2) Non-strategic decision of the SC; (3) Technology type/production philosophy; (4) Environmental condition of the model; and (5) Objective of mode, which includes LSC and other kinds of SC. Ugochukwu *et al.* (2012) states, "*When Lean is implemented across the entire SC, the SC is referred as a LSC*." Findings from the exhaustive review of Anand and Kodali (2008) show that previous studies concentrated on transforming the current FSC into LSC, rather than building a brand new LSC in its design stage.

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This study enumerates up to 59 LM tools/techniques available for LSC transformation. They are classified into four categories: (1) IT-based; (2) SCM-based; (3) Organization-based; and (4) JIT or LM elements.

Theoretically, the SCD process has been described through various models, in which the 5-stage SC Outline Process (SCOP) proposed by Corominas *et al.* (2015) profoundly draws out an SCD roadmap. To begin with, the first stage focuses on identifying the environment and objectives of the new SC. Further, stage 2 defines the SC macrostructure. Then, stage 3 identifies the SC mesostructure. Stage 4 specifies the SC microstructure, in which all SC specifications (objectives, parameters, constraints and variables) are formulated into mathematical models. Final stage chooses the optimal SC configuration among obtained results. There are two main solution methodologies in this stage: Exact solution and heuristics or MH (Melo *et al.*, 2008). Tiwari *et al.* (2010) realize the growing tendency of using MH as they can offer acceptably good solutions with relatively little CPU time. Especially, the application of MH in SCM and SCD is well reviewed by Stanley *et al.* (2012). The study finds that GA, a globally optimal MH inspired by evolutionary biology (Holland, 1962), is the most prevalent. During the time, GA is modified and hybridised with various algorithms in order to improve its search quality (Jaramillo *et al.*, 2002). Among of which, pGA, proves useful in designing the SC (Mitsuo *et al.* 2006). It is noteworthy that pGA is superior to Spanning Tree-based GA by using a simpler decoding procedure to generate random feasible chromosomes.

New Strategic Framework of LSCD

The new strategic framework of the LSCD includes three main stages and eight sub-steps (Fig. 1). To elaborate, suitable LM tools selected among 59 items in review of Anand and Kodali (2008) are implemented into the fourth and fifth stage of the SCOP model (Corominas *et al.*, 2015). These tools are classified into two categories that play a distinct role in the LSCD process: Functional Lean tools (which influence the SC total cost with daily operating functions) and Tier Lean tools (which affect the SC configuration), as depicted in Fig. 2. The entire process is particularly explained in turn below.

Formulate the FSC Model

The objective function of the FSC is to minimize the SC performance - Total Cost (TC), which is apportioned from SC tiers and functions as modified in study of Shretta *et al.* (2015), (Fig. 3a). The former include the Supplier (S), Plant (P), Distribution Centre (DC), Warehouse (WH) and Customer (C). The latter comprises five basic functions: Procurement, Production, Delivery, Inventory and Quality Assurance, which are described by the SC TC tree (Fig. 3b). Thus, the general FSC TC can be formulated from the five mentioned elements together with the Facility Installation cost. It is noted that all costs that are derived from suppliers are cumulated with the Material cost. Specifically, FSC TC is formulated in Equation 1 as follows:

$$FSC\ TC = Total\,Cost\left[Procurement + Production\right] + Inventory + Delivery + Quality + Installation \tag{1}$$

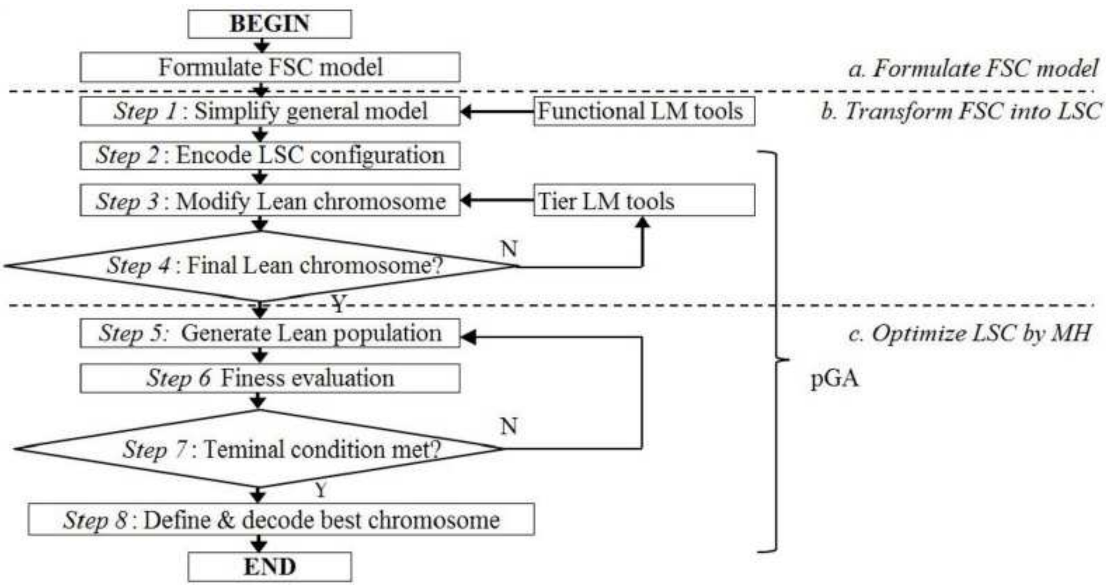


Fig. 1. Framework for optimizing the LSCD by the pGA

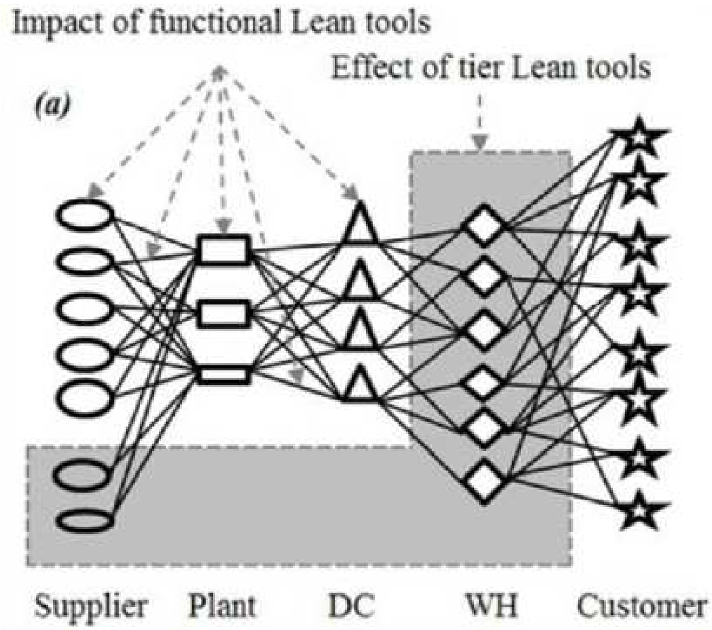


Fig. 2. Impact of Functional Lean tools and Tier Lean tools on the SC

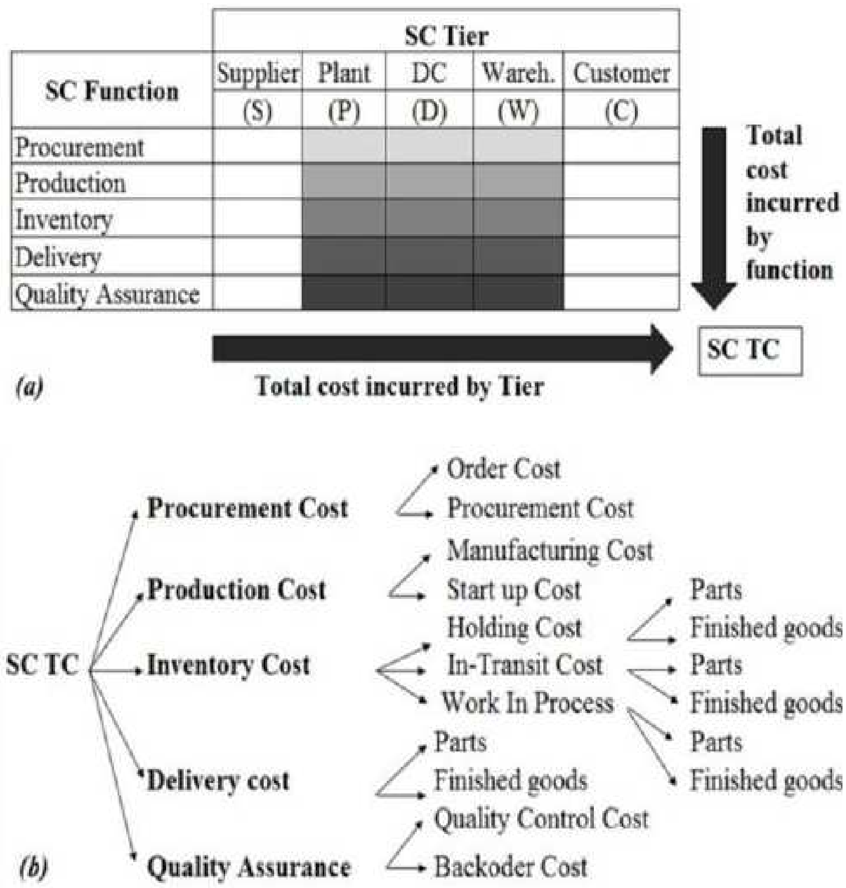
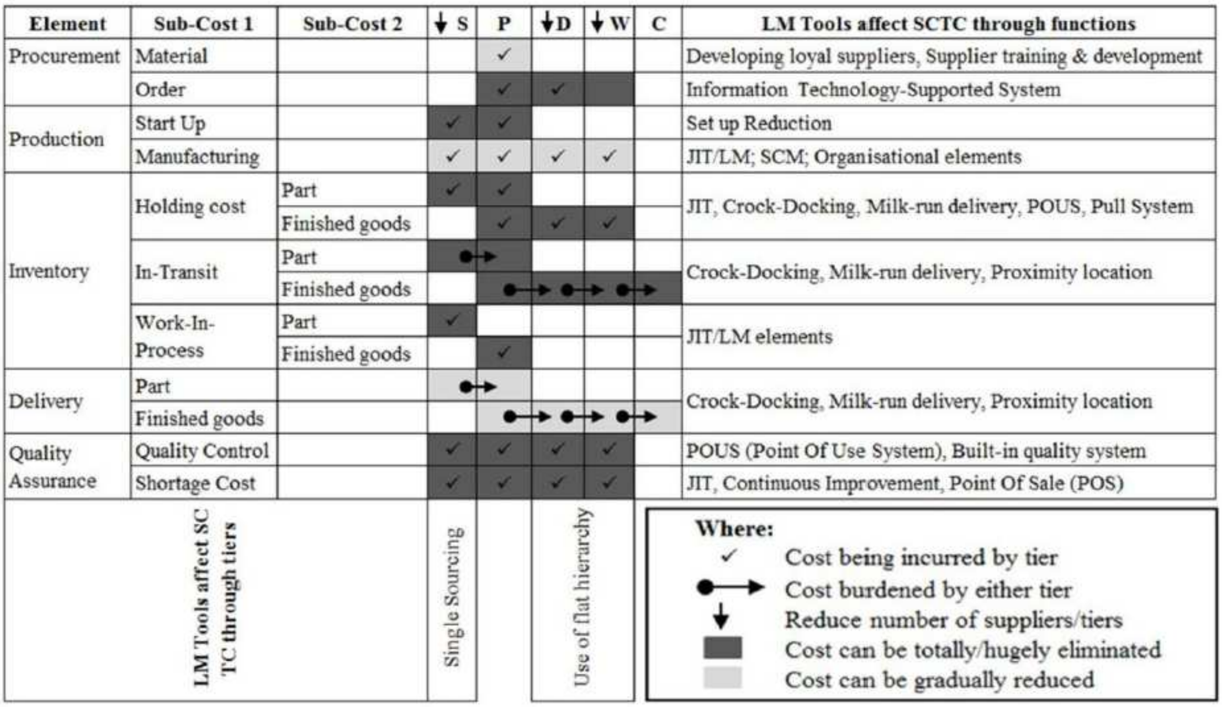


Fig. 3a. FSC TC by tier and function; 3b: SC TC tree



Element	Sub-Cost 1	Sub-Cost 2	↓S	P	↓D	↓W	C	LM Tools affect SCTC through functions
Procurement	Material			✓				Developing loyal suppliers, Supplier training & development
	Order			✓	✓			Information Technology-Supported System
Production	Start Up		✓	✓				Set up Reduction
	Manufacturing		✓	✓	✓	✓		JIT/LM; SCM; Organisational elements
Inventory	Holding cost	Part	✓	✓				JIT, Crock-Docking, Milk-run delivery, POUS, Pull System
		Finished goods		✓	✓	✓		
	In-Transit	Part	●→					Crock-Docking, Milk-run delivery, Proximity location
		Finished goods		●→	●→	●→		
	Work-In-Process	Part	✓					JIT/LM elements
		Finished goods		✓				
Delivery	Part		●→					Crock-Docking, Milk-run delivery, Proximity location
	Finished goods			●→	●→	●→		
Quality Assurance	Quality Control		✓	✓	✓	✓		POUS (Point Of Use System), Built-in quality system
	Shortage Cost		✓	✓	✓	✓		JIT, Continuous Improvement, Point Of Sale (POS)
LM Tools affect SC TC through tiers			Single Sourcing		Use of flat hierarchy			

Fig. 4. Framework of the LSC transformation

By substituting the SC TC structure in Fig. 3a and 3b into Equation 1, the FSC TC yields the following:

FSC TC

$$= Total\ Cost \begin{bmatrix} \left(Order_{PDW} + Raw\ Material_P\right) \\ +\left(Manufacturing_{PDW} + Start-Up_P\right) \\ +Holding\ \left(Parts_P + Finished\ Goods_{PDW}\right) \\ +\ In \\ -Transit\ \begin{pmatrix} Parts_{S-P} \\ +Finished\ Goods_{P-D,D-W,W-C} \end{pmatrix} \\ +WIP_P) \\ +Delivery\ \left(Finished\ Goods_{P-D,\ D-W,\ W-C}\right) \\ +Quality\ Control_{PDW} + Backoder_{PDW} \\ +Installation_{PDW} \end{bmatrix} \quad (2)$$

LSC Transformation

Step 1: Simplify the General Model with Functional Lean Tools (Fig. 4)

After a period of time, if these tools are strictly implemented, they can reduce various SC costs to some extent (completely, remarkably, or gradually). For example, Order cost, Setup cost and Holding/work-in-process cost can be almost eliminated by the *IT support system*, *Setup Reduction* and *JIT-based element* respectively. Similarly, the In-transit and Quality Assurance costs are hugely cut down by the *Proximity Location* and *Built-in Quality System/Point of Sale*. Thus, these costs are almost removed out of the TC model in the long run. As a result, Equation 2 remains with only four components: Raw Material, Manufacturing, Delivery and Installation cost. Therefore, the TC of the LSC is simplified from Equation 2 as follows:

LSC TC

$$= Total\ Cost \begin{bmatrix} Raw\ Material_P + Manufacturing_{PDW} \\ +Delivery\ \left(Finished\ Goods_{P-D,D-W,W-C}\right) \\ +Installation_{PDW} \end{bmatrix} \quad (3)$$

At the operational level, the objective function Equation 3 can be expressed by mix integer programing as:

$$Min\,LSC\,TC = \begin{bmatrix} \sum_I \sum_J R_{ij} y_{ij} + \left(\sum_J F_j x_j + \sum_I \sum_J V_j y_{ij}\right) \\ +\left(\sum_K F_k x_k + \sum_J \sum_K V_k y_{jk}\right) \\ +\left(\sum_L F_l x_l + \sum_K \sum_L V_k y_{kl}\right) \\ +\begin{pmatrix} \sum_J \sum_K T_{jk} y_{jk} + \sum_K \sum_L T_{kl} y_{kl} \\ +\sum_L \sum_M T_{lm} y_{lm} \end{pmatrix} \\ +\left(\sum_J I_j x_j + \sum_K I_k x_k + \sum_L I_l x_l\right) \end{bmatrix} \quad (4)$$

Where:

R_{ij}:	Unit Material cost of plant j with supplier i
F_j, F_k, F_l:	Annual fixed Operating cost of plant j, DC k, warehouse l
V_j, V_k, V_l:	Unit variable Operating cost of plant j and unit Throughput cost of DC k, warehouse l
T_{jk}, T_{kl}, T_{lm}:	Unit Transportation cost among adjacent tiers
I_j, I_k, I_l:	Installation cost of plant j, DC k and warehouse l
C_j, C_k, C_l:	Capacity of plant j and DC k and warehouse l
D_j, D_k, D_l, D_m:	Demands from plant j, DC k, warehouse l and customer l

Variables

x_j, x_k, x_l:	Binary variable denotes plant j, DC k, warehouse l opened (1) or closed (0)
y_{ij}, y_{jk}, y_{kl}, y_{lm}:	Quantity of material/product shipped among adjacent tiers

Subject to:

- Balance between quantities received and amount supplies at each node:

$$\sum_I y_{ij} = \sum_K y_{jk}; \sum_J y_{jk} = \sum_L y_{kl}; \\ \sum_K y_{kl} = \sum_M y_{lm} \tag{5}$$

- Satisfy demand from plant, DC, warehouse and customers:

$$\sum_I y_{ij} = D_j; \sum_J y_{jk} = D_k; \sum_K y_{kl} = D_m \tag{6}$$

- The quantity delivered from each node is less/equal to its capacity:

$$\sum_K y_{jk} \le C_j; \sum_L y_{lk} \le C_k; \sum_M y_{lm} \le C_l \tag{7}$$

- Non-negative conditions:

$$y_{ij}, y_{jk}, y_{kl} \ge 0 \tag{8}$$

Step 2: Encode the LSC Configuration

After simplified, the LSC is encoded by the pGA procedure as in study of Mitsuo *et al*. (2006) to identify its optimal configuration. The 5-tier SC is encoded through a 7-substring chromosome, in which the first, second and third substrings contain binary variables (open/close plants, DC and WH). The last four adjacent substrings denote transport trees between supplier and plant; plant - DC; DC - WH; then finally, WH and customer. These strings contain |I+J|, |J+K|, |K+L| and |K+M| digits with random values from 1 to |I+J|, |J+K|, |K+L| and |K+M| respectively (Fig. 5a).

Step 3: Modify the Lean Chromosome

When Tier Lean tools are applied, they impact the amount of node/tier in the SC, which changes its denoted chromosome. Particularly, the application of *Single Sourcing* reduces the number of suppliers to one for each component type. Hence, the supplier-plants transport substring is removed because its configuration becomes deterministic (Fig. 5b). Similarly, the *Use of Flat Hierarchy* can minify the intermediary tiers in the supplier-plant or/and plant-customer substrings. Thus, the correlative substrings of these tiers are deleted. Figure 5c represents the chromosome of the LSC when *Single Sourcing* is used and the warehouse stage is flatted. LSC objective in Equation 4 becomes:

$$Min\,LSC\,TC = \begin{bmatrix} \sum_I \sum_J R_{ij} y_{ij} + \left(\sum_J F_j x_j + \sum_I \sum_J V_j y_{ij} \right) \\ + \left(\sum_K F_k x_k + \sum_J \sum_k V_k y_{jk} \right) \\ + \left(\sum_J \sum_K T_{jk} y_{jk} + \sum_K \sum_M T_{km} y_{km} \right) \\ + \left(\sum_J I_j x_j + \sum_K I_k x_k \right) \end{bmatrix} \tag{9}$$

Step 4: Final Lean Chromosome?

The quantity of Tier Lean tools applied depends on the deliberate goals of SC designers. Thereby, the denoted chromosome is correspondingly leaned until the design requirements are met. For instance, other techniques such as *Group Technology*, *Use of Common Part* and *Modularity* are able to change product structure by decreasing the types of components purchased from subcontractors. So, they reduce number of suppliers and genes on chromosomes simultaneously.

Optimise LSC by pGA

Step 5: Generate Lean Population Pool

Heuristically, pGA uses the same procedure as GA to randomly generate and handle the offspring in a population pool.

Step 6: Fitness Evaluation

After created, each offspring is decoded to the transportation tree in order to calculate the fitness (LSC TC). In pGA, each gene on a chromosome has two factors: Locus and allele. Locus is the position of genes denoting the order of source/destination in the transportation tree. Meanwhile, the gene value of allele bears represents the priority level of nodes assigned to the transportation tree. The decoded procedure determines the highest allele on a chromosome. Its corresponding locus is referred to the node having the priority to be served or delivered.

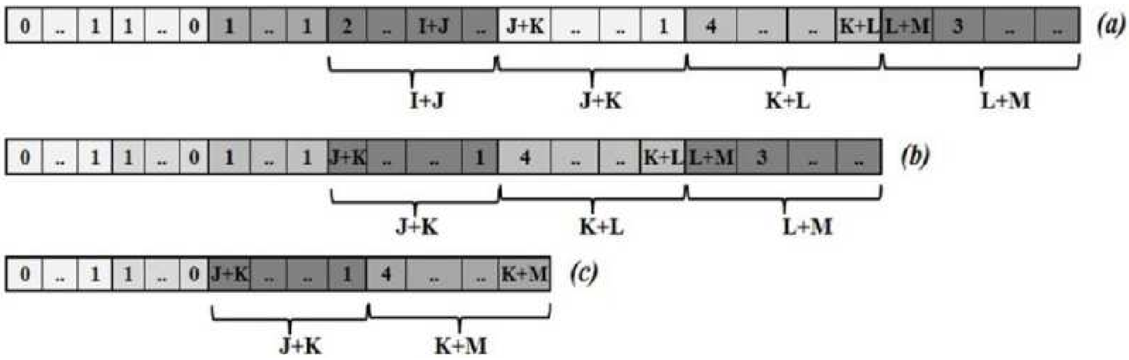


Fig. 5a. General LSC chromosome; (b) LSC chromosome while using *Single Sourcing*; (c) LSC chromosome while applying *Single Sourcing* and the *Use of Flat Hierarchy*

Then, the shipment from this node with its counterpart is established, provided that the transportation cost between them in the cost matrix is the lowest. When any node is completely supplied/ served, its correlative allele is assigned to zero. The assignment repeats until all alleles on the chromosome adopt the null value. At that time, the transportation tree is totally built and the fitness is computed based on this network.

Step 7: Terminated Condition Met?

The terminated condition can be set similar to the GA.

Step 8: Define and Decode the Best Chromosome

Finally, the chromosome contributing to the best fitness is defined and then decoded in order to identify the best configuration of the LSC.

Illustrative Example

To illustrate the aforementioned method, one numerical example of the LSC design is described step by step. Assuming that all information in Step 1, 2 and 3 of the SCOP model is defined, the designers outline one potential FSC structure including 7 suppliers, 4 plants, 5 DCs and 8 WHs to serve 8 customers, in which supplier 1 and 2 provide the same components as supplier 6 and 7. While examining three assumptions and collected data in Table 1 and 2, the managers want to lean both the supply side and the demand side, with only 5 suppliers, 3 plants, 4 DCs, 6 WHs selected. Assumptions:

- Suppliers' capacities satisfy demands of all plants
- Customers' demands are deterministic and must be satisfied completely
- All the transportation links between adjacent tiers are available

Step 1: Simplify the General Model

Designers intend to implement Functional Lean tools in Fig. 3 into their draft of the FSC. When transformed, the LSC TC contains four factors like Equation 3.

Step 2: Encode the LSC Configuration

With I = 5, J = 3, K = 4, L = 6 and M = 8, the chromosome of the LSC structure is randomly denoted with 7 substrings, 56 digits (Fig. 6).

Step 3: Modify the Lean Chromosome

When *Single Sourcing* is applied, supplier 6 and 7 are dropped (their material cost higher than competitors'), so their supplies are transferred to supplier 1 and 2 (the forth substring is removed). Since the supply side is leaned, *The Use of Flat Hierarchy* is then used to clear the warehouse tier (substrings WH and D-W are wiped out). Thus, DCs serve customers directly and the last substring W-C turns out as D-C. The LSC chromosome is then modified as Fig. 7.

Step 4: Final Lean Chromosome?

In this case, other Tier Lean tools have not been applied. Therefore, the chromosome representing the LSC structure defined in Step 3 is final.

Step 5: Generate Lean Population

The mutation and crossover rates are set at 0.1 and 0.8 respectively.

Step 6: Fitness Evaluation

Lean chromosomes are decoded to compute the fitness from Equation 10:

$$Min\,LSCTC = \begin{bmatrix} \sum_5 \sum_3 R_{ij} y_{ij} + \left(\sum_3 F_j x_j + \sum_5 \sum_3 V_j y_{ij} \right) \\ + \left(\sum_4 F_k x_k + \sum_4 \sum_3 V_k y_{jk} \right) \\ + \left(\sum_3 \sum_4 T_{jk} y_{jk} + \sum_4 \sum_8 T_{km} y_{km} \right) \\ + \left(\sum_3 I_j x_j + \sum_4 I_k x_k \right) \end{bmatrix} \quad (10)$$

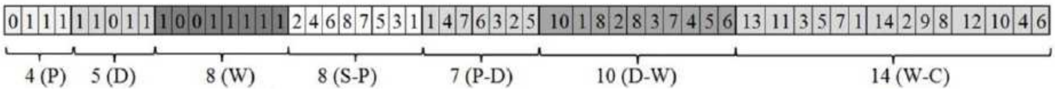


Fig. 6. One example chromosome of the LSC while using Functional Lean tools

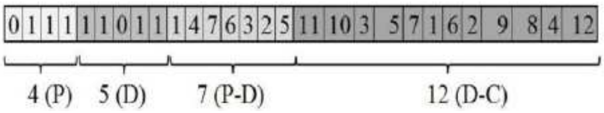


Fig. 7. Random LSC chromosome while using *Single Sourcing* and *The Use of Flat Hierarchy*

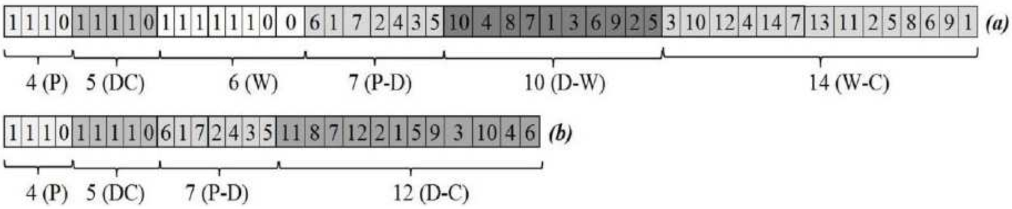


Fig. 8. (a) Best LSC chromosome under the Functional Lean tools effect; (b): Final LSC chromosome

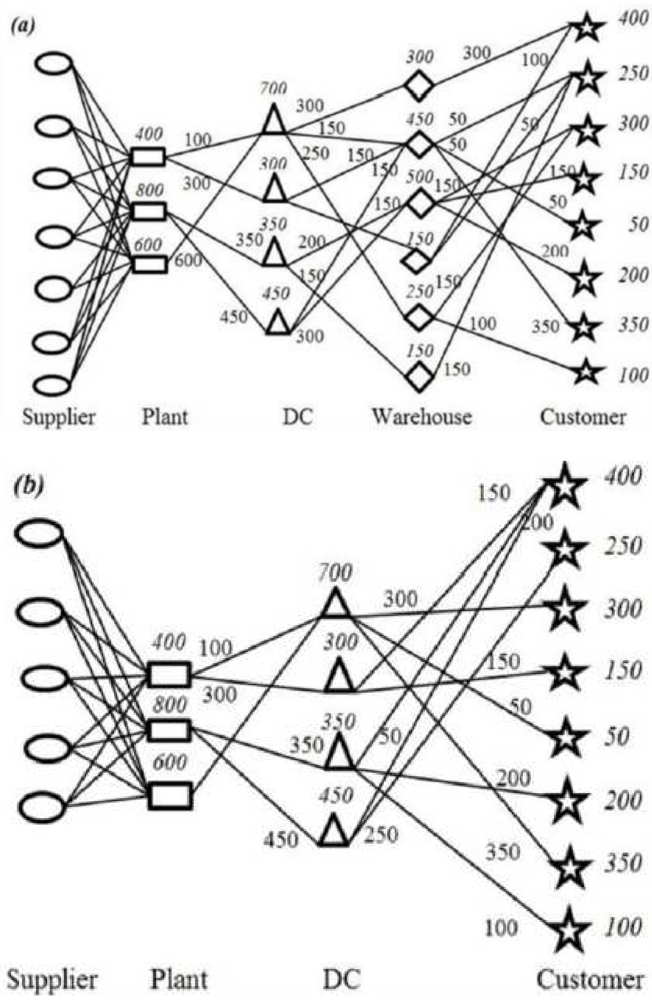


Fig. 9. (a) Best LSC under the Functional Lean tools effect; (b) Final LSC configuration

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Table 1. SC data

	Plant					DC					Warehouse					
No	Dj	Cj	Fj	Vj	Ij	Dk	Ck	Fk	Vk	Ik	Dl	Cl	Fl	Vl	Il	Cus Dm
1	400	500	50,000	25	700,000	700	550	13,200	8,250	245,000	300	350	5,100	2,400	52,500	400
2	800	900	108,000	30	1,400,000	300	800	19,200	12,000	105,000	450	500	7,650	3,600	78,750	250
3	600	750	75,000	28	1,050,000	350	500	12,000	7,500	122,500	500	600	8,500	4,000	87,500	300
4	800	1,000	116,000	35	1,480,000	450	300	7,200	4,500	157,500	150	200	2,550	1,200	26,250	150
5						700	450	10,800	6,750	315,000	250	300	4,250	2,000	43,750	50
6											150	250	2,550	1,200	26,250	200
7											300	350	5,100	2,400	58,500	350
8											150	200	2,850	1,200	29,250	100

Table 2. SC cost matrix

	S1	S2	S3	S4	S5	D1	D2	D3	D4	D5	C1	C2	C3	C4	C5	C6	C7	C8	
											18.5	19.6	16.7	16.8	15.3	20.1	15.4	18.9	D1
P1	123.2	129.8	120.4	134.5	132.1	11.3	12.4	13.3	12.7	19.8	17.4	16.8	15.8	15.4	16.8	19.5	16.4	21.4	D2
P2	146.5	150.3	139.2	146.4	148.1	16.3	13.2	14.3	12.1	18.4	16.7	18.3	19.4	15.8	18.5	17.4	15.8	20.4	D3
P3	135.7	137.5	136.4	143.6	129.5	10.5	12.7	11.1	14.7	16.3	15.6	15.2	20.1	17.7	16.4	17.2	21.3	15.7	D4
P4	155.4	168.2	163.3	170.4	161.3	11.8	14.7	14.8	15.1	15.2	18.2	24.1	23.4	17.9	18.7	20.6	22.7	24.5	D5
					W1	5.4	6.2	7.3	9.4	11.5	4.3	5.4	6.8	6.2	5.2	5.7	4.8	4.7	
					W2	7.8	6.4	5.9	8.7	10.6	5.6	5.9	4.1	5.7	4.8	6.3	5.2	7.2	
					W3	10.3	9.5	10.1	6.3	10.4	6.4	6.2	5.3	4.4	5.1	4.6	6.3	4.8	
					W4	8.8	5.7	6.3	5.8	9.5	4.7	6.3	5.5	6.1	4.8	5.2	4.4	7.3	
					W5	6.5	8.4	9.2	7.7	10.5	6.9	6.8	4.1	5.9	6.6	4.3	5.6	4.1	
					W6	8.2	5.9	8.2	7.3	8.8	5.3	4.6	6.4	5.3	4.8	5.8	6.7	5.5	
					W7	7.9	8.7	9.8	9.3	11.4	4.8	5.7	6.6	4.5	5.9	6.1	5.8	4.7	
					W8	8.7	9.2	10.7	10.6	11.5	4.2	6.2	5.3	4.7	6.5	4.6	6.9	5.4	

Step 7: Terminated Condition Met?

The iteration is set at 1000.

Step 8: Define and Decode the Best Chromosome

The best chromosome of the LSC affected by Functional Lean tools in Step 2 is in Fig. 8a, while the optimal one of final LSC is depicted in Fig. 8b. Following this, they are decoded to the best corresponding LSC configurations in Fig. 9a and 9b. The results show that the final structure is much leaner than both FSC and LSC, which are leaned by Functional tools. Concerning fitness, the minimum LSC TC in two situations achieves $6,198,035 and $5,332,175 in turn. On the other hand, the implementation of both Functional and Tier Lean tools reduce the LSC TC by up to 16.24% when compared with the cost of the LSC leaned by Functional tools only.

Conclusion

The paper presents in detail one new quantitative framework to optimise the design of LSC by Meta-Heuristics through three main stages: Forming the FSC model; transforming the FSC into LSC; and optimizing the LSCD with pGA. The particular point of this study is that it classifies LM tools into Functional Lean tools and Tier Lean tools. This classification contributes to two important findings: The framework of the LSC transformation through Functional Lean tools and the integration of Tier Lean tools with pGA to optimise the LSC structure. The solutions from the numerical example prove that this novel approach benefits both the LSC configuration and financial aspects. Moreover, this procedure can clearly draw out a general roadmap for designers, which could assist them in designing their LSC in a quantitative approach. It also offers a reference for the managing cadre in order to flexibly select proper Lean tools that will serve their business objectives.

Along with the selected LM tools in the given instances, other LM techniques related to product design like *Modularity*, *Group Technology* and *Use of Common Parts* also affect the SC structure. Further studies can focus on these areas in order to optimise the conformity of LSC configuration with the product structure.

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Author's Contributions

Thi Hong Dang Nguyen: Conduct the research, prepare the manuscripts and do any revisions.

Thien My Dao: Instruct research directions and qualify the solutions; give final approval of the version to be submitted and any revised versions.

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Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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