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Location-inventory problem in supply chains: a modelling review

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A location-inventory problem (LIP) aims to integrate strategic supply chain design decisions with tactical and operational inventory management decisions. This study provides an extensive review of the existing literature of LIP modelling. A mathematical model is presented for a basic LIP, which can be further developed to incorporate additional features for use in real-world scenarios. We also discuss the evolution of LIP modelling literature over the past three decades and provide summary tables outlining characteristics of the published works including key modelling attributes and objective function cost components. Additional classifications are completed based on the solution methods adopted and real-world applications investigated. Our observations provide important insights and identify potential directions for future research in the field.

Keywords: location-inventory problem; facility location; inventory management; strategic supply chain design; tactical and operational planning; review

1. Introduction

The supply chain (SC) structure or topology has substantial influences on how businesses execute strategies and gain sustainable competitive advantages. Strategic decisions related to SC structure including determining the location and capacity of facilities are typically made for a planning horizon of two to five years (Zokaee, Jabbarzadeh, et al. 2014). Determining the location of airports, restaurants, schools, hospitals, manufacturing plants and distribution centres (DCs) is amongst the more common strategic SC decisions. Tactical planning decisions (e.g. production and distribution planning, demand planning) and operational planning decisions (e.g. shop-floor scheduling, inventory planning, transportation planning) are reliant on supply, manufacturing, transportation and storage costs and capacities which in turn are highly influenced by strategic location decisions (Farahani, Miandoabchi, et al. 2013; Esmaeilikia et al. 2014b).

Strategic, tactical and operational decisions have traditionally been made in a hierarchical sequence due to the different nature, scope and timeline of the encountered problems Fahimnia, Parkinson, et al. (2013). This sometimes results in multiple conflicting and unfeasible decisions, calling in the need for integrated multi-level decision-making, despite the inherent modelling complexities (Fahimnia, Farahani, et al. 2013; Jabbarzadeh, Fahimnia, and Seuring 2014). In addition, in a highly dynamic business environment, decisions at the strategic level may need to be revisited for enhanced SC efficiency once tactical and operational plans are developed (Fahimnia, Luong, and Marian 2012), a 'closed-loop planning approach' we name it.

Cost-based measures have been the predominant performance metric in tackling facility location problems (Farahani and Hekmatfar 2009). The primary cost components in a facility location problem include location, transportation and inventory costs. Essentially, the trade-off between these costs is a major undertaking in SC network design problems (Pishvaee, Basiri, and Sajadieh 2009). A common approach to tackling the modelling complexities of a facility location problem is to simplify the situation by breaking a large problem into smaller sub-problems (Stadtler 2008). However, such approaches may produce two locally optimal solutions that minimise location and inventory costs in isolation, not necessarily resulting in a global optimum. On the other hand, joint location-inventory problems (LIPs) may turn into large complex optimisation problems requiring sophisticated solution methods to solve. Advances in technology (e.g. fast speed processors) and the emergence of new sophisticated solution techniques to solve nonlinear and large linear mathematical models have enabled researchers and practitioners to deal with increasingly larger and more complex integrated planning problems (Fahimnia, Farahani, et al. 2013; Esmaeilikia et al. 2014a).

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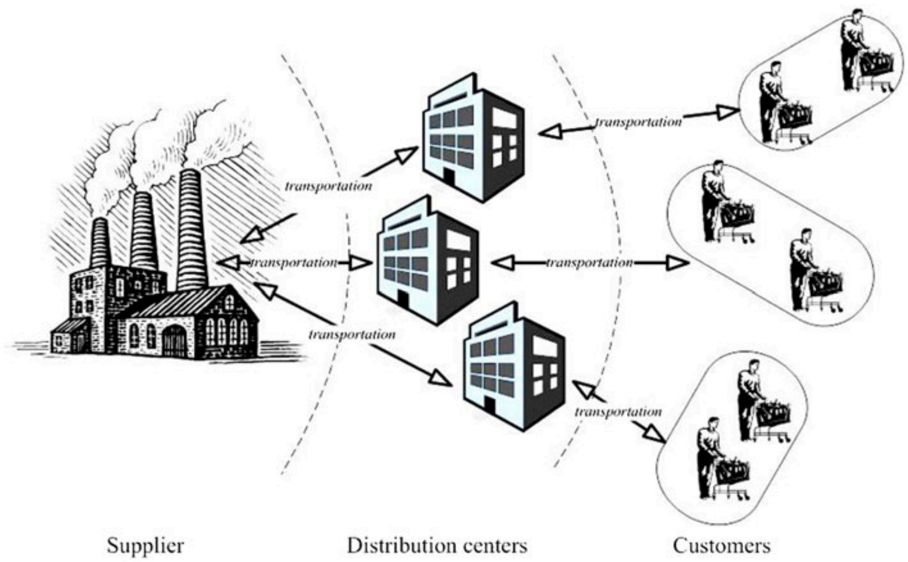

Figure 1. A three-layer location-inventory problem.

Figure 1 illustrates a three-layer LIP. The network involves suppliers providing a set of products to DCs, which eventually fulfil the product demands at multiple customer locations. A typical LIP assumes the predetermined location of suppliers and aims to determine the optimal number and the location of DCs, allocate customers to DCs and optimise the inventory service level at each DC (Daskin, Coullard, and Max Shen 2002). Transportation and routing decisions can also be added to a standard LIP, though in reality these decisions have rarely been made in an integrated manner. Perl and Sirisoponsilp (1988) were amongst the first to develop an integrated model incorporating inventory, location and transportation decisions, but the model was not validated using numerical experiments. Another example is the work of Jayaraman (1998) which investigates the trade-off between inventory, location and transportation decisions to seek an optimal distribution network design.

Facility location models can be classified based on their applications such as hub facility location, hierarchical facility location, P-median, P-centre, covering, noxious/obnoxious facility location, dynamic/multi-period facility location and dispersion models. Another classification can be based on the solution methods developed and approaches undertaken to solve these problems. A number of review papers have been completed in the past few years attempting to classify the published facility location models based on either application type or techniques used. For example, Farahani, SteadieSeifi, and Asgari (2010) review the techniques used in multi-criteria decision-making models. Farahani et al. (2012) review popular strategies, applications and techniques in covering problems such as capacitated, covering tour, path covering, multiple coverage, backup coverage, covering location–interdiction, partial coverage and gradual coverage. Boloori and Farahani (2012) classify statistic, dynamic and multi-period facility location problems into continuous facility location problems (single, multiple and location–allocation), discrete facility location problems (plant location and quadratic assignment) and network facility location problems (median, covering, centre, hub and hierarchical). Models, applications and solution techniques of hub network facility location problem are reviewed by Alumur and Kara (2008) and Farahani, Hekmatfar, et al. (2013). Similarly, hierarchical facility location models are reviewed by Şahin and Süral (2007) and Farahani, Hekmatfar, et al. (2014).

The above reviews focus on location problem as an important strategic decision. However, there are other strategic decisions such as capacity planning and allocation decisions that, in concert with a location problem, can compound SC network design problems. A comprehensive review of the literature of published SC network design models can be found in Farahani, Rezapour, et al. (2014). Reviews have also been completed in other facility location areas such as dynamic facility location models (Boloori and Farahani 2012), sustainability in facility location (Chen, Olhager, and Tang 2014), facility location at the SC level (Melo, Nickel, and Saldanha-da-Gama 2009) and congestion models for facility location (Boffey, Galvão, and Espejo 2007).

Unlike these review papers that focus merely on strategic SC decision-making, the current paper aims to complete a review of the models that integrate strategic facility location decisions with operational inventory management decisions. Management of all inventory types, such as cycle inventory, safety stock, production inventory and end of period inventory, falls into the scope of this paper. The earlier modelling efforts in this context looked at the integration benefits at the organisational level. Only more recently has the focus shifted to exploring the opportunities, challenges and benefits of strategic-operational decision-making at the SC level. To the best of our knowledge, no review has been completed on identifying and classifying the published LIP models and investigating the evolution of this rapidly growing research area. In this paper, we present the key characteristics of the published LIP models in summary tables and provide additional classifications based on the solution methods adopted and real-world applications investigated. Current research trends and suggested directions for future research in the field will conclude this paper.

2. LIP modelling

The four primary types of LIPs include the basic LIP, dynamic-location-inventory problem (DLIP), location-inventory-routing problem (LIRP) and inventory-transportation problem (ITP). We first present a mathematical model for the basic LIP, which is the core of all four LIP types. We consider a three-level single commodity network where a single supplier fulfils the product demand at retailers through a set of DCs. We use similar assumptions presented in Tanonkou et al. (2005). A general assumption in LIP is that several retailers offer similar products, and so, it may be efficient to consider one retailer as the depot to serve others. The problem is to find the best location for DCs so that the retailers can be served at the minimum inventory holding and transportation cost, also taking into consideration DC establishment cost. Demands and delivery lead times are considered non-deterministic and are assumed to follow a normal distribution pattern. The parameters and decision variables used for the formulation of the models are presented in Table 1.

Using these parameters and decision variables, the basic LIP can be formulated as:

Table 1. Parameters and decision variables used for modelling of the basic LIP.

Parameters	
i	Index for retailer, $i \in I$, where I is the set of retailers
j	Index for DC, $j \in I \vert j \leq J$, where J is the set of DCs
v	Index for vehicle, $v \in V$, where V is the set of vehicles
A_j	Ordering cost at jth DC
H_j	Unit holding cost at jth DC
T_j	Total available product at jth DC
Q_j	Order size at jth DC
D_j	Annual demand at jth DC
F_j	Fixed cost of locating jth DC
l_j	Mean of delivery lead time from the supplier to jth DC
δ_j^2	Variance of delivery lead time from the supplier to jth DC
μ_i	Mean of demand at ith retailer
σ_i^2	Variance of demand at ith retailer
t_j	Unit transportation cost from the supplier to jth DC
t_{ij}	Unit transportation cost from ith retailer to jth retailer
z_α	Standard normal deviate such that $P(Z \leq z_\alpha) = \alpha$, where α is the service level at DCs
ψ	Number of working days per year
b_v	Capacity of vth vehicle
h_i^+	Cost of carrying inventory in ith retailer
h_i^-	Shortage cost in ith retailer
β_i	Initial inventory level at ith retailer
w_i	Quantity delivered to ith retailer
$q_i(0)$	Inventory cost function in ith retailer
$C_i(0)$	Cumulative demand distribution function in ith retailer
Variables	
X_j	Binary variable, equals 1 if jth retailer is considered as a DC; 0 otherwise
Y_{ij}	Binary variable, equals 1 if ith retailer is served by jth DC; 0 otherwise
Z_{ijv}	Binary variable, equals 1 if vth vehicle drives from ith to jth retailer; 0 otherwise
$\Re_{iv}$	Binary variable, equals 1 if ith retailer is assigned to vth route; 0 otherwise

$$\text{Min} \sum_j F_j X_j + \psi \sum_i \sum_j t_j \mu_i Y_{ij} + \psi \sum_i \sum_j t_{ij} \mu_i Y_{ij} + \sum_j \left(A_j \frac{D_j}{Q_j} + H_j \frac{Q_j}{2} \right) + z_\alpha \sum_j H_j \sqrt{\sum_i l_j \sigma_i^2 Y_{ij}} + z_\alpha \sum_j H_j \sqrt{\sum_i \delta_i^2 (\mu_i Y_{ij})^2} \quad (1)$$

Subject to

$$\psi \sum_i \mu_i Y_{ij} = D_j \quad \forall j \quad (2)$$

$$\sum_j Y_{ij} = 1 \quad \forall i \quad (3)$$

$$Y_{ij} \leq X_j \quad \forall i, j \quad (4)$$

$$Y_{ij}, X_j \in \{0, 1\} \quad \forall j, k \quad (5)$$

The objective function (1) presents the total cost of the system consisting of five terms. Term 1 is the fixed cost of locating DCs. Terms 2 and 3 express transportation costs from the supplier to DCs and from DCs to retailers, respectively. Terms 4–6 present inventory-related costs, including costs of holding inventory and safety stock as well as shortage costs. Constraint (2) calculates the annual demand at each DC. Constraints (3) and (4) ensure that each retailer is assigned to one open DC. Equation (5) enforces the binary nature of the decision variables.

The basic LIP model presented here could be used for different purposes and investigated from different angles. For example, Eppen (1979) for the first time compared centralised and decentralised inventory systems. Nozick and Turnquist (1998) study an automobile case study to analyse the effect of safety stock inventory cost on locating DCs. A one-to-one inventory replacement model is presented for single-level inventory holding. Sourirajan, Ozsen, and Uzsoy (2007) examines a two-stage SC network to locate DCs that considers the trade-off between lead times and safety stocks. Ozsen, Coullard, and Daskin (2008) shows that the capacitated warehouse location problem with risk pooling can be neither concave nor convex. Yang, Ng, and Cheng (2010) examine the impacts of locational decisions at DCs on the SC profit margins. Schmitt (2011) studies service-level protection risks in a multi-layer SC. Agrali, Geunes, and Taskın (2012) introduce a mixed-integer nonlinear programming model for the LIP where uncapacitated facilities are linear in form.

A range of different variables and constraints has been incorporated in the published LIP models. Jayaraman (1998) determines the number and location of plants and warehouses in a network where retailers have deterministic demand for multiple products. Capacitated plants, capacitated warehouse space and transshipment modes are other characteristics of this model. Barahona and Jensen (1998), Zhang and Huo (2005) and Halvorsen-Weare and Kjetil (2013) develop similar LIP models with various finite and infinite capacities. Considering order size constraints in addition to inventory capacity constraints, Miranda and Garrido (2008) develop a LIP model to determine the location of DCs, the order size of DCs and the assignment of retailers with stochastic demands to DCs. Using a similar approach, Mahar, Bretthauer, and Venkataramanan (2009) studies a four-layer network (including a supplier, a central warehouse, several stores and demand nodes) that seeks to find the optimal location of stores to satisfy online and in-store stochastic demands while minimising the location, transshipment, inventory holding and backordering costs. Firoozi et al. (2013) consider quantity discount as an inventory policy, and Silva and Gao (2013) incorporate inventory replenishment costs at the DCs. Wijk, Adan, and van Houtum (2012), and Shavandi and Bozorgi (2012) study LIP models with Poisson and fuzzy demand, respectively.

There are also studies that focus on the development of solution methods to tackle the related problems. Erlebacher and Meller (2000) utilise a heuristic approach to determine the optimal number of DCs in a two-level single-period single-product LIP. Max Shen, Coullard, and Daskin (2003) convert a nonlinear integer-programing LIP model to a set-covering integer-programing model and solve it using a column generation algorithm. They conclude that wherever the demands of retailers are known or the variance of demand is proportional to the mean, the problem can be solved in polynomial time. Daskin, Coullard, and Max Shen (2002) propose a Lagrangian relaxation method to solve the same problem. While the algorithm fails to reach optimality, they apply two variable fixing rules in the form of a branch-and-bound algorithm. The efficiency of this method is investigated by comparing the results with the set partitioning and column generation methods. Wang, Sun, and Yang (2005) present a non-linear mixed-integer model for a multi-echelon distribution network problem and a Lagrangian relaxation and sub-gradient solution method. The Lagrangian relaxation approach has also been used by Miranda and Garrido (2004, 2006, 2008) to tackle a stochastic SC network problem aiming to simultaneously minimise location, inventory and transportation costs for a given service level. Miranda and Garrido (2004) address an extended version of the capacitated facility location problem with stochastic demands and risk pooling effect. Miranda and Garrido (2006) add the concept of stochastic capacity to a formerly published LIP model. They further extend their work (Miranda and Garrido 2008) by adding two ordering and inventory capacity constraints and find that an optimal solution can be easier to find at smaller order sizes.

2.1 *Extended LIP models*

2.1.1 *DLIP models*

DLIPs are regarded as NP-hard problems and are used to deal with situations when changes occur in allocation costs over multiple periods of a planning horizon (Khumawala and Whybark 1976). We do not wish to present a general DLIP model in this section as DLIP models may vary considerably based upon the assumptions considered. Interested readers may refer to the following studies to gain insights into modelling efforts in this arena. Erlenkotter (1981) compare seven approximation approaches for dynamic location problems in both continuous-time and discrete-time horizons. Lim, Kim, and Correspondence (1999) present a mixed-integer linear programing model for determining the capacity and the location of plants in a dynamic environment. Viswanadham and SrinivasaRaghavan (2000) investigate procurement and delivery operations in a dynamic SC model utilising generalised stochastic Petri nets. Melo, Nickel, and Saldanha da Gama (2006) evaluate the performance of a DLIP model from several aspects such as distribution network structure, inventory management, dynamic relocation of facilities and investments opportunities. Hinojosa et al. (2008) extend the model of Jayaraman (1998) to incorporate the dynamic nature of the order size and the planning horizon. Gebennini, Gamberini, and Manzini (2009) present a stochastic location–allocation problem that incorporates dynamic inventory, production rates and service level.

2.1.2. *LIRP models*

We present a mathematical model that combines vehicle routing and inventory allocation problems (adopted from the work of Federgruen and Zipkin 1984). The proposed routing-inventory problem takes into account the routing costs between retailers in addition to the inventory costs incurred at retailers. The inventory-related cost for *i*th retailer is defined in equation (6), which is the summation of inventory holding and shortage costs.

$$q_i(w_i) = \int_0^{\beta_i+w_i} h_i^+(\beta_i + w_i - x)dC_i(x) + \int_{\beta_i+w_i}^{\infty} h_i^-(x - \beta_i - w_i)dC_i(x) \tag{6}$$

The general mathematical model of LIRP can be presented as:

$$\text{Min} \sum_i \sum_j \sum_v t_{ij} Z_{ijv} + \sum_i q_i(w_i) \tag{7}$$

Subject to

$$\sum_i w_i \Re_{iv} \leq b_v \quad \forall v \tag{8}$$

$$\sum_i w_i Y_{ij} \leq T_j \quad \forall j \tag{9}$$

$$Z_{ijv} \leq Y_{ij} \quad \forall v \tag{10}$$

$$\sum_v \Re_{iv} = 1 \quad \forall i \tag{11}$$

$$\sum_j Z_{ijv} = \Re_{iv} \quad \forall i, v \tag{12}$$

$$\sum_i Z_{ijv} = \Re_{jv} \quad \forall j, v \tag{13}$$

$$\sum_i \sum_j Z_{ijv} \leq I - J \quad \forall v \tag{14}$$

$$\Re_{iv}, Z_{ijv}, Y_{ij} \in \{0, 1\} \quad \forall i, j, v \tag{15}$$

The objective function (7) minimises the travel and inventory costs. Constraint (8) enforces the capacity limitation of vehicles. Constraint (9) ensures the availability of items at the DC. Constraint (10) ensures that each route is set based on the assignment of retailers to DCs. Constraint (11) assigns each customer to one transport route. Constraints (12)–(14) are the sub-tour elimination constraints.

Liu and Lee (2003) present a single-product multiple-DC LIRP model. A heuristic solution approach is designed that tackles location–allocation and transportation/inventory problems in that order. In another study, the authors compare their method with the existing solution techniques (Liu and Lin 2005). Ambrosino and Grazia Scutellà (2005) present a case study to discuss two LIRP mathematical models. Ma and Davidrajuh (2005) study LIRP in an agile environment in which the outputs of operational decisions provide feedback to strategic decision-making. Max Shen and Qi (2007) solve a LIRP model where customer demand follows a certain stochastic probability. A hybridised heuristic model is developed by Ahmadi Javid and Azad (2010) where location–allocation, inventory and routing problems are integrated using stochastic capacity constraints. Mete and Zabinsky (2010) apply the LIRP concept with a stochastic programming to a disaster planning problem. Lieckens, Colen, and Lambrecht (2012) present a strategic decision support tool for the supply of repairable service parts in a multi-product multi-level network.

2.1.3. *Inventory-transportation problem*

From a mathematical point of view, ITPs are similar to LIRPs; however, these models do not directly incorporate location decisions, but focus more on adjustment of service level requiring a trade-off between backordering, holding and transportation costs. Several ITP models incorporating a range of decision-making criteria have been presented in the past (see e.g. Rudi, Kapur, and Pyke 2001; Gen and Syarif 2005; Hu, Watson, and Schneider 2005; Özdemir, Yücesan, and Herer 2006; Wang, Yao, and Huang 2007; Pujari, Hale, and Huq 2008; Kutanoglu and Mahajan 2009; Li and Zhang 2012; Özdemir, Yücesan, and Herer 2012). More recently, the consideration of possible delays in transportation has gained increasing interest amongst researchers. For example, Kiesmüller, de Kok, and Fransoo (2005) evaluate the possibility of postponement in transportation model decisions. Capar, Eksioglu, and Geunes (2011) develop a decision tool to select a DC in a periodic-review system in a two-stage SC network. Hochmuth and Köchel (2012) present a simulation model to study a multi-location-inventory system with lateral transshipment.

3. Characteristics of the published LIP models

We used the ‘title, abstract, keywords’ search of the Scopus database and attempted the keywords ‘inventory’, ‘location’, ‘transportation’ and ‘SC’ to search for the related LIP-published models. Figure 2 illustrates a year-based classification of the papers found in this search attempt. The evolution clearly shows the increasing popularity of this research area, especially after 2005. Also, the discipline-based classification of these studies, graphically depicted in Figure 3, shows that over 50% of all the published models have appeared in four subject areas including environmental sciences, earth and planetary sciences, agricultural and biological sciences, and engineering. This is an indicator of the breadth of LIP modelling applications and the critical role engineering scholars have in providing modelling tools and solution techniques to tackle the encountered problems.

Several attributes can be used to describe a LIP model. Table 2 outlines the general attributes, which we use to highlight the characteristics of the published LIP models. The planning horizon, order size, and capacity of plants and DCs could be considered either finite or infinite. Periodic-review models split the planning horizon into several discrete periods, and inventory decisions are made and implemented at the end of each period. Conversely, in a continuous-review model, decisions are made continuously over time. The number of DCs can be either calculated by the model (endogenous) or given as input parameters (exogenous). Demand at end-users or customer locations could be either deterministic (i.e. fixed and known) or stochastic (i.e. random variables with known probability distributions). Shipping costs can be obtained as a function of the type of shipment, distance between facilities, order size, combined shipment function and order size, or combined distance and order size. Distance between facilities and demand points can be calculated using different functions (Zarinbal 2009), but rectilinear and Euclidean methods are the most popular approaches. LIP models could also be developed for single or multiple product types.

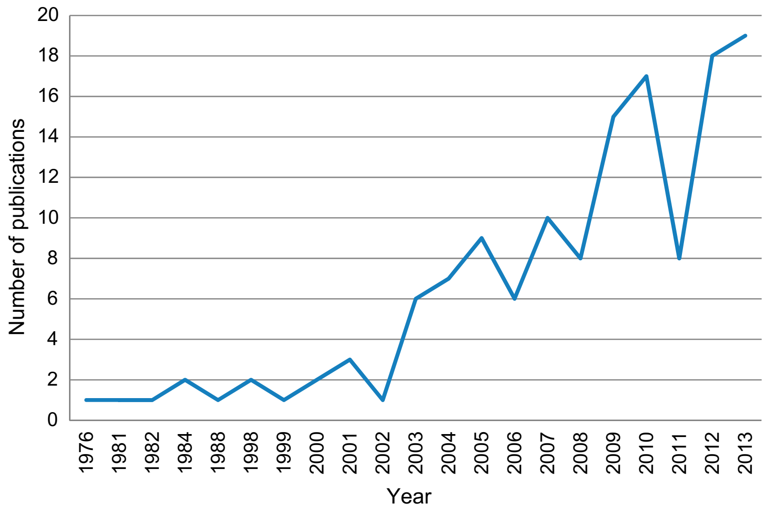

Figure 2. The evolution of the published LIP models (1976–2013).

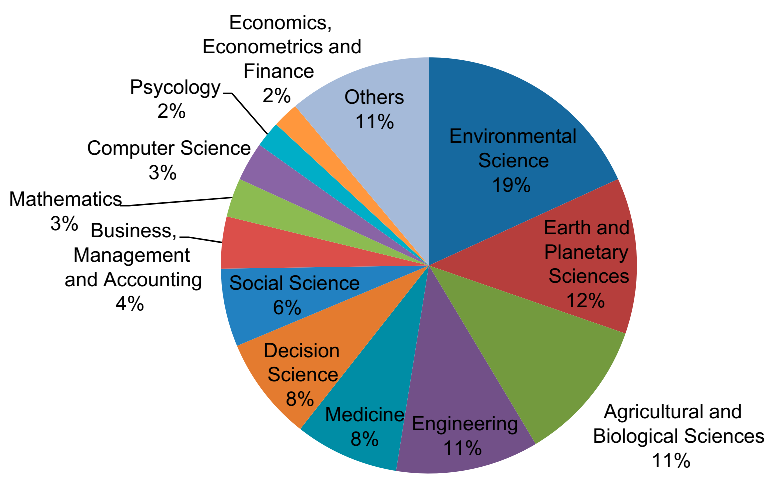

Figure 3. The contribution of different subject areas to published LIP models (1974–2013).

Given the modelling attributes outlines in Table 2, Table 3 summarises the characteristics of the proposed models. Some studies such as the work of Chandra (1993) that proposes a multi-period model to determine the quantity of commodities and the optimal route to customers can be classified under both LIRP and DLIP models. However, we have only included in Table 3 those studies that involve locational decisions; otherwise, they are considered out of scope and excluded from this classification.

Typical objective function cost components in a LIP model include the following. *Locating costs* include the one-off fixed costs incurred for establishing facilities. *Facility operating costs* are the periodic costs of materials, designing, building and maintaining facilities. *Inventory holding cost* is the cost of carrying items from one period to another and is typically a function of product quantity and holding duration. *Ordering costs* include transaction fees, salaries of purchasing staff, phone calls and other costs related to placing and processing orders, typically independent of the order quantity. *Safety stock cost* is the cost incurred for holding extra items to deal with demand variations, usually a combination of opportunity and storage costs. *Backordering cost* is a penalty cost incurred when customer demand is not fulfilled in one period, an indicator of service level. Backordered demand is satisfied sooner or later during the planning horizon. *Shortage cost* or the cost of lost sale is incurred if demand cannot be satisfied during the planning horizon. *Shipment cost* includes the costs related to loading, picking and packing products in DCs. *Transportation cost* between

Table 2. General attributes of LIP models.

	Attribute	Symbol
Type of model	Location-inventory problem	LIP
	Dynamic-location-inventory problem	DLIP
	Location-inventory-routing problem	LIRP
	Inventory-transportation problem	ITP
Horizon	Finite	F
	Infinite	I
Inventory policy	Continuous review	C
	Periodic review	P
Plant capacity	Finite	F
	Infinite	I
DC capacity	Finite	F
	Infinite	I
Number of DCs	Endogenous	En
	Exogenous	Ex
Demand type	Deterministic	D
	Stochastic	S
Shipping cost	Function of distance	DF
	Function of order size	OF
	Function of distance & order size	D&OF
	Function of shipment mode & order size	S&OF
Distance calculation	Rectilinear	R
	Euclidean	E
Product	Single product	S
	Multi-product	M
Order size capacity	Finite	F
	Infinite	I
Solution method	Classical and analytical	CA
	Heuristic and Meta-heuristic	HM
	Other methods	O

facilities is typically a function of distance travelled and quantity of items shipped. In this context, *routing* refers to selection of the appropriate routes from a set of possible distribution channels.

4. Classification based on solution techniques

Different methodologies have been developed and adopted to solve the LIP models. We classify these into three categories: classical and analytical methods (also known as exact methods), heuristic and meta-heuristic methods, and other methods. Table 4 presents a classification of the existing literature based on the solution techniques used.

4.1 *Classical and analytical solution methods*

Classical and analytical (CA) methods that have been used to tackle LIP models include branch and bound (B&B), column generation (CG), dynamic programming (DP) and generalised benders' decomposition (GBD). B&B is the most widely used amongst all. In many CA methods, Lagragian relaxation (LR) is adopted to simplify the developed optimisation problems. Van Roy and Erlenkotter (1982) propose a combination of B&B and dual ascent methods to solve a DLIP. Barahona and Jensen (1998) apply a sub-gradient optimisation in a Dantzig–Wolfe (D-W) decomposition method based on LR. Jayaraman (1998) uses the GAMS modelling package to solve the LIP. Daskin, Coullard, and Max Shen (2002) use LR embedded in a B&B to find lower and upper bounds of DC capacity that is used for DC exchange algorithm and reassigning of retailers. Max Shen and Qi (2007) present an LR method using a B&B engine. They introduce an algorithm in polynomial order and solve a nonlinear integer problem through LR sub-problems. Mahar, Bretthauer, and Venkataramanan (2009) present two algorithms to solve a LIP model including static and dynamic assignment algorithms. The optimal dynamic assignment method is shown to be able to reduce the network cost by 8% of the optimal static assignment.

Table 3. Characteristics of the published LIP models.

	General attributes											Objective function cost components										
Author (year)	Type of model	Horizon	Inventory policy	Plant capacity	DC capacity	Number of DCs	Demand type	Shipping cost	Distance calculation	Product	Order size capacity	Locating cost	Facility operating cost	Inventory holding cost	Ordering cost	Safety stock cost	Backordering cost	Shortage cost	Service level	Routing	Shipment cost	Transportation cost
Federgruen and Zipkin (1984)	LIRP	I	C	F	–	–	S	DF	–	S	F			●	●			●		●		
Singh and Vrat (1984)	LIP	I	C	I	I	Ex	S	D&OF	E	S	I				●			●				●
Barahona and Jensen (1998)	LIP	I	–	I	I	En	D	DF	–	M	I	●			●							●
Jayaraman (1998)	LIP	I	C	F	F	En	D	S&OF	–	M	I	●			●							●
Nozick and Turnquist (1998)	LIP	I	–	I	I	En	S	DF	–	S	I	●	●		●	●						●
Tagaras (1999)	ITP	I	P	I	F	Ex	S	OF	–	S	F			●	●		●				●	●
Xu (1999)	LIP	I	C	I	I	Ex	S	DF	–	S	I	●			●							●
Erlebacher and Meller (2000)	LIP	I	C	I	I	En	D	D&OF	R	S	I	●	●	●	●				●			●
Nozick and Turnquist (2001a)	LIP	I	–	I	I	En	S	DF	–	S	I	●		●	●			●			●	●
Nozick and Turnquist (2001b)	LIP	I	C	I	I	En	S	D&OF	–	S	I	●			●				●		●	●
Rudi, Kapur, and Pyke (2001)	ITP	F	C	F	F	Ex	D	S&OF	–	S	F				●						●	●
Daskin, Coullard, and Max Shen (2002)	LIP	I	C	I	I	En	S	OF	–	S	I	●			●	●						●
Liu and Lee (2003)	LIRP	I	C	I	I	En	D	DF	–	S	F	●			●							●
Max Shen, Coullard, and Daskin (2003)	LIP	I	F	I	I	Ex	D	OF	–	S	F	●			●	●					●	●
Miranda and Garrido (2004)	LIP	F	C	I	F	En	S	DF	–	S	I	●	●	●	●							●
Ambrosino and Grazia Scutellà(2005)	LIRP	I	C	I	F	En	D	D&OF	–	S	F	●			●						●	●
Gen and Syarif (2005)	ITP	F	–	F	I	Ex	D	DF	–	M	I	●		●	●						●	●
Hu, Watson, and Schneider (2005)	ITP	F	C	I	I	Ex	D	D&OF	–	S	I			●	●			●			●	●
Liu and Lin (2005)	LIRP	I	C	I	I	En	D	D&OF	–	S	F	●			●							●
Ma and Davidrajuh (2005)	LIRP	I	C	F	F	En	S	D&OF	–	S	F	●		●		●			●		●	●
Tanonkou et al. (2005)	LIP	I	C	I	I	En	S	D&OF	–	S	I	●	●		●	●						●
Wang, Sun, and Yang (2005)	LIP	I	C	I	I	En	S	OF	–	S	I	●	●	●	●	●						●
Zhang and Huo (2005)	LIP	I	C	F	I	En	D	D&OF	–	M	I	●			●				●			●
Gabor and van Ommeren (2006a)	LIP	I	–	I	I	En	S	D&OF	–	S	I	●		●								●
Gabor and van Ommeren (2006b)	LIP	I	P	I	I	Ex	S	OF	–	S	F		●		●							●
Melo, Nickel, and Saldanha da Gama (2006)	DLIP	F	C	I	F	En	D	OF	–	M	F	●	●	●							●	●
Miranda and Garrido (2006)	LIP	I	C	I	F	En	S	OF	–	S	F	●	●	●		●						●
Özdemir, Yücesan, and Herer (2006)	ITP	F	C	I	I	Ex	D	D&OF	–	S	F				●			●			●	●
Tanonkou, Benyoucef, and Xiaolan (2006)	LIP	F	C	I	I	En	S	D&OF	–	S	I	●		●	●	●					●	

(*Continued*)

Table 3. (*Continued*).

	General attributes											Objective function cost components										
Author (year)	Type of model	Horizon	Inventory policy	Plant capacity	DC capacity	Number of DCs	Demand type	Shipping cost	Distance calculation	Product	Order size capacity	Locating cost	Facility operating cost	Inventory holding cost	Ordering cost	Safety stock cost	Backordering cost	Shortage cost	Service level	Routing	Shipment cost	Transportation cost
Berman, Krass, and Menezes (2007)	LIP	I	–	I	I	En	D	–	–	S	I	●		●	●		●				●	
Chew, Lee, and Rajaratnam (2007)	LIP	I	C	I	F	En	S	D&OF	–	S	F			●	●							●
Max Shen and Qi (2007)	LIRP	I	C	I	I	En	S	OF	–	S	I	●			●						●	
Snyder, Daskin, and Teo (2007)	LIP	I	C	I	I	En	S	D&OF	–	S	I	●		●	●						●	●
Sourirajan, Ozsen, and Uzsoy (2007)	LIP	I	C	I	F	En	S	OF	–	S	I	●				●						
Tanonkou, Benyoucef, and Xiaolan (2007)	LIP	I	C	I	I	En	S	D&OF	–	S	I	●		●	●	●					●	●
Tang, Yang, and Yang (2007)	LIP	I	C	I	I	En	D	D&OF	–	S	I	●			●							●
Wang, Yao, and Huang (2007)	ITP	I	C	I	I	Ex	S	D&OF	–	S	I			●	●		●				●	●
Xin-hua and Jin (2007)	LIP	F	C	I	F	En	S	D&OF	–	S	F	●	●	●	●							●
Hinojosa et al. (2008)	DLIP	F	C	F	F	En	D	D&OF	–	M	F	●	●	●								●
Miranda and Garrido (2008)	LIP	I	C	I	F	En	S	OF	–	S	F	●	●		●	●						●
Ozsen, Coullard, and Daskin (2008)	LIP	I	C	I	F	En	S	OF	–	S	F	●		●	●	●		●			●	●
Pujari, Hale, and Huq (2008)	ITP	I	C	F	–	–	–	OF	–	S	–	●	●	●							●	●
Tanonkou, Benyoucef, and Xiaolan (2008)	LIP	I	C	I	I	En	S	D&OF	–	S	I	●		●	●	●					●	●
ÜSter, Keskin, and ÇEtinkaya (2008)	LIP	I	P	F	F	En	D	OF	E	M	I			●	●						●	●
Diabat, Aouam, and Al-Araidah (2009)	LIP	I	C	I	I	En	D	OF	–	S	F	●		●	●	●			●		●	●
Gebennini, Gamberini, and Manzini (2009)	DLIP	F	P	F	I	En	S	D&OF	E	S	F	●			●		●					●
Ghezavati, Jabal-Ameli, and Makui (2009)	LIP	I	C	I	I	Ex	S	OF	–	S	F	●		●	●			●			●	
Jeet, Kutanoglu, and Partani (2009)	LIP	I	C	F	F	En	S	D&OF	E	S	I	●	●	●		●			●			●
Kutanoglu and Mahajan (2009)	ITP	I	C	I	I	Ex	S	OF	–	S	I	●		●								●
Liao and Hsieh (2009)	LIP	I	C	F	F	Ex	S	OF	–	S	F	●	●			●			●			●
Mahar, Bretthauer, and Venkataramanan (2009)	LIP	I	C	I	I	En	S	OF	–	S	I			●			●					●
Mak and Max Shen (2009)	LIP	F	C	F	F	En	S	OF	–	S	F	●		●	●		●				●	
Miranda and Garrido (2009)	LIP	I	P	–	F	Ex	S	OF	–	S	F	●		●	●	●		●	●			●
Sourirajan, Ozsen, and Uzsoy (2009)	LIP	I	C	–	F	En	D	OF	–	S	–	●			●	●						●
Bashiri and Tabrizi (2010)	LIP	I	P	F	F	Ex	S	DF	E	S	F			●	●	●						●

Bretthauer, Mahar, and Venakataramanan (2010)	LIP	I	P	F	F	En	D	S&OF	–	S	I	●	●	●			●				●	●
Ahmadi Javid and Azad (2010)	LIRP	I	C	F	F	En	S	OF	–	S	F	●		●	●	●				●	●	
Keskin, Üster, and Çetinkaya (2010)	LIP	I	C	F	F	En	D	OF	–	S	F	●									●	●
Liu, Zhou, and Zhang (2010)	LIP	I	P	F	F	Ex	D	OF	–	S	F	●			●							●
Mete and Zabinsky (2010)	LIRP	I	P	F	F	En	S	D&OF	–	S	F	●				●				●		●
Nasiri, Davoudpour, and Karimi (2010)	LIP	I	C	F	F	Ex	S	D&OF	E	M	F	●		●		●						●
Rezapour and Farahani (2010)	LIP	F	P	F	F	Ex	D	D&OF	E	S	F	●									●	●
Shu, Ma, and Li (2010)	LIP	I	C	–	–	Ex	S	DF	E	S	F	●		●	●						●	●
Yao et al. (2010)	LIP	I	P	F	F	En	S	S&OF	E	M	F					●			●			●
Bogataj, Grubbström, and Bogataj (2011)	LIP	I	C	F	F	Ex	D	D&OF	E	–	F	●			●							●
Chen, Li, and Ouyang (2011)	LIP	I	P	F	F	En	D	OF	–	S	F	●			●							●
Conceicao et al. (2011)	LIP	F	C	F	F	Ex	D	D&OF	E	S	F	●		●			●					●
Schmitt (2011)	LIP	I	P	F	F	Ex	S	OF	–	S	F							●		●		●
Shavandi and Bozorgi (2012)	LIP	I	C	F	F	En	D	OF	–	S	I	●		●								●
Jha et al. (2012)	LIP	F	–	F	F	En	D	DF	–	M	F	●										●
Lieckens, Colen, and Lambrecht (2012)	LIRP	F	C	I	I	En	S	S&OF	–	M	I	●	●	●						●	●	●
Nasr, Salameh, and Moussawi-Haidar (2012)	ITP	I	–	–	F	Ex	S	OF	–	S	F			●		●						●
Sajady and Davoudpour (2012)	LIP	I	C	F	F	En	D	S&OF	–	M	F	●		●								●

Table 4. Solution techniques used in the literature of LIP modelling.

Author (year)	Class	Technique used	Reference	Class	Technique used
Federgruen and Zipkin (1984)	HM	Interchanges and GBD	Wang, Yao, and Huang (2007)	CA	Lower bound
Singh and Vrat (1984)	HM	Iterative	Xin-hua and Jin (2007)	HM	SA
Barahona and Jensen (1998)	CA	Sub-gradient D-W	Hinojosa et al. (2008)	HM	LR
Jayaraman (1998)	CA	LR and B&B	Miranda and Garrido (2008)	HM	LR
Nozick and Turnquist (1998)	HM	Greedy	Ozsen, Coullard, and Daskin (2008)	HM	LR
Tagaras (1999)	HM	Simulation-grid search	Pujari, Hale, and Huq (2008)	O	Continuous approx
Xu (1999)	HM	Substitutional heuristic	Tanonkou, Benyoucef, and Xiaolan (2008)	HM	LR
Erlebacher and Meller (2000)	HM	LR	ÜSter, Keskin, and ÇEtinkaya (2008)	HM	Hybrid heuristic
Nozick and Turnquist (2001a)	HM	Greedy	Diabat, Aouam, and Al-Araidah (2009)	HM	Heuristic
Nozick and Turnquist (2001b)	HM	Greedy	Gebennini, Gamberini, and Manzini (2009)	CA	Recursive procedure
Rudi, Kapur, and Pyke (2001)	HM	Nash equilibrium	Ghezavati, Jabal-Ameli, and Makui (2009)	HM	GA & rule based
Daskin, Coullard, and Max Shen (2002)	CM	LR and B&B	Jeet, Kutanoglu, and Partani (2009)	CA	Outer approx
Liu and Lee (2003)	HM	A two-phase heuristic	Kutanoglu and Mahajan (2009)	CA	Implicit enumeration
Max Shen, Coullard, and Daskin (2003)	CA	CG	Liao and Hsieh (2009)	HM	Hybrid GA
Miranda and Garrido (2004)	HM	LR	Mahar, Bretthauer, and Venkataramanan (2009)	CA	Static & dynamic assignment
Ambrosino and Grazia Scutellà (2005)	CA	Lower bound	Mak and Max Shen (2009)	HM	LR
Gen and Syarif (2005)	HM	HST-GA	Miranda and Garrido (2009)	HM	Sequential heuristic
Hu, Watson, and Schneider (2005)	CA	DP	Sourirajan, Ozsen, and Uzsoy (2009)	HM	GA & LR
Liu and Lin (2005)	HM	TS & SM	Bashiri and Tabrizi (2010)	HM	POS
Ma and Davidrajuh (2005)	HM	Iterative heuristic	Bretthauer, Mahar, and Venakataramanan (2010)	CA	B&B
Tanonkou et al. (2005)	HM	LR	Ahmadi Javid and Azad (2010)	HM	SA & TS
Wang, Sun, and Yang (2005)	HM	LR & sub-gradient	Keskin, Üster, and Çetinkaya (2010)	CA	GBD
Gabor and van Ommeren (2006a)	O	Reduction approx	Liu, Zhou, and Zhang (2010)	HM	LR
Gabor and van Ommeren (2006b)	O	Two approx	Mete and Zabinsky (2010)	HM	Deterministic equivalent
Melo, Nickel, and Saldanha da Gama (2006)	CA	Lower bound	Nasiri, Davoudpour, and Karimi (2010)	CA	LR & sub-gradient
Miranda and Garrido (2006)	HM	LR	Rezapour and Farahani (2010)	CA	Modified projection
Özdemir, Yücesan, and Herer (2006)	O	IPA	Shu, Ma, and Li (2010)	CA	CG
Tanonkou, Benyoucef, and Xiaolan (2006)	HM	LR & SAA	Yao et al. (2010)	HM	Iterative heuristic
Chew, Lee, and Rajaratnam (2007)	HM	GA	Chen, Li, and Ouyang (2011)	HM	LR
Max Shen and Qi (2007)	CA	LR and B&B	Conceicao et al. (2011)	CA	DSS
Snyder, Daskin, and Teo (2007)	CA	LR	Shu et al. (2012)	CA	Branch & Price
Sourirajan, Ozsen, and Uzsoy (2007)	HM	LR	Melo, Nickel, and Saldanha-da-Gama (2012)	HM	TS
Tanonkou, Benyoucef, and Xiaolan (2007)	CA	LR	Shavandi and Bozorgi (2012)	HM	GA
Tang, Yang, and Yang (2007)	HM	LR & GA	Tsao et al. (2012)	O	Continuous approx

Table 5. Real-world applications of LIP models.

Author (year)	Case study and place
Nozick and Turnquist (1998)	Distribution system for finished automobiles – North America
Altiparmak et al. (2006)	Producers of plastic products in Europe
Sousa, Shah, and Papageorgiou (2008)	Agrochemicals
Gebennini, Gamberini, and Manzini (2009)	Production and distribution of electronic components in Italy
Conceicao et al. (2011)	Steel industry in Latin America
Najafi et al. (2011)	Locating disaster relief centres in Middle-East
Rawls and Turnquist (2011)	Emergency response for hurricane threats
Rezapour, Farahani, and Drezner (2011)	Flour production and distribution SC in Middle-East
Stasko et al. (2011)	Forest-biomass SC in North America
Tabata et al. (2011)	Fossil fuel (coal) industry in Asia
Xu, Wermus, and Bauman (2011)	Medical/healthcare SC
Yang and Lu (2011)	Thin film transistor-liquid crystal display manufacturing
You and Wang (2011)	Biomass-to-liquids (BTL) SC in North America
Cardoso et al. (2013)	European SC
Robb et al. (2012)	Manufacturing SC in Asia
Lieckens, Colen, and Lambrecht (2012)	Remanufacturing services

Keskin, Üster, and Çetinkaya (2010) develop a mixed-integer nonlinear programming (MINLP) model incorporating several properties including the DC selection, transportation costs between vendors and stores, and the inventory-related costs based on the classical economic order quantity (EOQ). A GBD solution method was used to solve the problem. Bretthauer, Mahar, and Venakataramanan (2010) determine the appropriate locations of online sales to minimise the total costs for satisfying both in-store and online demand. Berman, Krass, and Tajbakhsh (2012) present a coordinated LIP with periodic-review inventory policy allowing for both partial and full coordination. The proposed nonlinear integer programming (NLIP) formulation is tackled using a LR-based solution method. More recently, Coelho and Laporte (2013) developed a branch-and-cut algorithm to solve a LIP model aiming to improve the order satisfaction rate.

4.2 *Heuristic and meta-heuristic solution methods*

Heuristic and meta-heuristic (HM) methods have been adopted to deal with nonlinear problems and large linear problems that are not solvable (or are subject to heavy computing overhead) using standard exact solution methods (Fahimnia, Farahani, et al. 2013; Fahimnia, Farahani, and Sarkis 2013). Greedy algorithms, dropping, adding, substitution and exchange of elements of model are amongst the common heuristic techniques in the context of LIP modelling. The most popular meta-heuristic methods used to tackle complex LIP models include Lagrangian relaxation (LR), genetic algorithm (GA), simulated annealing (SA) and tabu search (TS) solutions methods.

Miranda and Garrido (2006) develop a heuristic algorithm based on LR and a sub-gradient method to solve an NP-hard problem with nonlinear objective function and constraints. A standard forward linear prediction (FLP) method cannot tackle a nonlinear model with nonlinear components in the objective function and constraints. To overcome this, Miranda and Garrido (2008) present a complex greedy heuristic and a local improvement procedure, which could be applied to a subset of iterations only. Erlebacher and Meller (2000) propose a set of simplification rules to design an analytical method and use restrictions on the number and capacity of DCs to reduce the search area. They also use heuristics to obtain the optimal assignment of retailers to DCs. A stochastic programming model was presented by Mete and Zabinsky (2010) to tackle a LIP in the first stage and a disaster routing problem in the second stage. Yao et al. (2010) propose a heuristic to solve a MINLP location–allocation and inventory problem. Chen, Li, and Ouyang (2011) apply a LR-based heuristic method to locate facilities, allocate customers and make inventory decisions. Gen and Syarif (2005) present a meta-heuristic named hybridised spanning tree-based genetic algorithm (HST-GA) combining fuzzy logic controller with GA parameters. Bashiri and Tabrizi (2010) present a particle swarm optimisation (PSO) to solve a holistic SC network design problem. Shavandi and Bozorgi (2012) develop a LIP model in a fuzzy environment and a GA-based solution technique to solve the problem. Guerrero et al. (2013) have recently applied a hybrid heuristic method to solve a mixed LIP model with deterministic demand.

4.3. *Other solution methods*

The other solution methods used for solving LIP models cannot be classified under either CA or HM solution methods. Such methods as simulation and approximation-based techniques are amongst these. For example, Özdemir, Yücesan, and Herer (2006) use infinitesimal perturbation analysis (IPA) to estimate the optimal level of multi-location transshipment problems with transportation capacities. Based on a Monte Carlo optimisation approach, Tanonkou, Benyoucef, and Xiaolan (2006) combine the sample average approximation (SAA) with a heuristic to solve a network design problem. Tsao et al. (2012) apply a two-phase continuous approximation method to determine location/allocation decisions in a network design problem.

5. Real-world applications of LIP modelling

Despite the broad real-world applications of LIP models, surprisingly, only a small number of published papers have used real data to investigate the utility of the proposed models and solution techniques. Table 5 outlines the studies that have used real data to investigate the real-world application of the models and solution techniques. While the origin of LIP modelling dates back to about 30 years ago, it can be seen that a vast majority of real case studies have only been published during the past few years. We see this as a promising trend showing the increasing interest of industry practitioners in the topic and researchers to investigate the actual application of the models developed.

6. Conclusions and directions for further research

We presented a thorough review of the LIP modelling efforts and showed the evolution of the literature over three decades as well as the contribution of different knowledge areas to this rich research area. Characteristics of the published models were presented in terms of general modelling attributes and incorporated cost components in the objective function. Classifications were completed based on the solution methods adopted and real-world applications investigated. From these classifications, we firstly observe that most of the published models and mathematical formulations do incorporate binary and integer variables. Secondly, amongst the four primary types of LIPs (including basic LIP, DLIP, LIRP and ITP), more focus has been placed on the modelling of basic LIPs. This might be due to the inherent modelling complexity of incorporating a range of variables and constraints at different planning levels. Another observation is that most of the studies consider an infinite time horizon, which is, again, a way to simplify the more difficult models with finite time horizon. Lastly, continuous review has been the predominant inventory policy with only few studies attending the development of periodic-review models.

We identify some clear research trends in the field. The incorporation of realistic features in LIP modelling can be the most notable research trend. More models are attempting the incorporation of finite storage and transportation capacities, routing and transportation costs, finite time horizons, and secondary objectives such as service level, and stochastic demand data. This is also evidenced by the trend in investigating the real-world application of the developed models with a large majority of case studies only published after 2011. In terms of trends in the use of solution techniques, GA, SA and TS have been the most popular in that order. One primary reason for the dominant use of these metaheuristic solution methods may be the straightforward and well-defined structure of these techniques, hence facilitating the effective and relatively fast design, coding and implementation of these algorithms.

From our comprehensive review and discussions, we identify the followings areas as potential directions for future research:

- The nature of the LIP modelling, particularly in the 'location' part, imposes the use of binary variables. Location problems can be solved on discrete, network or continuous space. A vast majority of published models study a discrete space. The diverse applications of LIP modelling suggest that network and continuous space problems can be a potential area for further research.
- LIP has been broadly studied as a static problem. However, the dynamic nature of input parameters is an undeniable characteristic of today's volatile business environment. The incorporation of uncertainty elements in critical input parameters such as cost, capacity and demand data can enhance the real-world application of the developed models.
- Solving LIRP and ITP models can result in additional cost savings compared to a basic LIP model. Such decisions are generally taken at different planning levels, and the associated modelling efforts may require the development of more complex heuristics solution methods.
- LIP modelling is completed for a planning horizon of [0, T], where T is a larger number in most strategic decision scenarios. Most of published models assume an infinite planning horizon, which is not a realistic assumption. In addition, in reality, we often face discrete-time horizons in which [0, T] is split into several smaller periods of equal lengths (e.g. years). The periodic-review and continuous-review (discrete) inventory policies can also be applied to 'location' problems of LIP modelling. Innovative solution techniques are required to tackle LIP models

with infinite planning horizons and periodic-review policies.

- Different distance functions can be adopted to more realistically calculate the travelling distance and transportation costs between SC nodes. Euclidean and rectilinear functions have been the most popular distance functions, but more realistic functions, possibly case based or sector based, can be utilised in future research (see Zarinbal 2009).
- The lack of case studies is another proof of 'oversimplification' in the developed models. Considering a realistic range of variables and constraints in developing LIP models may result in broader application of the developed models in real-world situations.
- Concurrent decision-making at multiple planning levels has been a rare occurrence in past research. The only few studies integrating inventory, location and transportation decisions at the strategic, tactical and operational levels include the recent works of Miranda and Garrido (2008), Mak and Max Shen (2009), Miranda and Garrido (2009), Gebennini, Gamberini, and Manzini (2009), Ahmadi Javid and Azad (2010), Jha et al. (2012), Naseraldin and Herer (2011), Diabat, Richard, and Codrington (2011) and Sajjadi and Cheraghi (2011).
- Backordering costs (due to delayed deliveries) and shortage costs (due to lost sales) have been considered in some of the past studies. However, the joint consideration of backordering and shortage costs in LIP modelling is non-existent.

Apart from the above research directions that can be observed from trends in the existing literature of LIP modelling, we also suggest more generic research directions derived from trends in the current business environment. (1) Given the emerging regulatory policies and increasing stakeholder pressures and incentives, development of multi-objective models in which sustainability, reliability, risk and service level can be incorporated as secondary objectives in addition to the traditional cost functions can be an important future research direction. (2) The broader acceptance of more push-based SC coordination strategies may result in pushing inventory holdings towards upstream in the SC. The LIP modelling efforts in such situations may be more complex in nature, but the findings can be very insightful, especially for SCs with more decentralised ownership. (3) One of the important applications of LIP models is in humanitarian operations where relief centres are located to serve people affected in disasters. Determining the optimal location of such facilities is a very challenging problem due to the high degree of supply and demand uncertainties. Inventory issues, on the other hand, are as important because large quantity of items, mostly perishable, may need to be stored in these facilities as safety stock for long time periods. De Leeuw, Kopczak, and Blansjaar (2010) presented one of the few models for shared stockpile design in humanitarian operations in which inventory can be utilised for multiple purposes including supplying patients in unforeseen events.

Overall, it is expected that this field will continue to grow as practitioners face integration challenges that research can help solve. Given the increasing interest of both academic researchers and practitioners in integrated strategic, tactical and operational decision-making, our review and discussions in this paper can help researchers establish their research agendas in LIP modelling research and more generally in multi-level decision-making research.

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