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Integrated transportation – inventory models: A review

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ABSTRACT

As decision-making practices in industry shift from isolated, unilateral department decisions to multiparty supply chain planning, integrated modelling techniques have risen in popularity. Models that simultaneously address transportation and inventory decisions have been of particular interest. This article reviews Integrated Transportation-Inventory (ITI) models developed over the last two decades for various supply chain configurations. Recurring topics in such models are discussed and those growing in popularity are identified. Features and constraints inherent in ITI models are categorized and analysed. Finally, research gaps are highlighted with a focus on further aligning academic interests with current and emerging industry practices.

1. Introduction

Inventory management has been studied by researchers and industry leaders alike for over a century. The Economic Order Quantity (EOQ), one of the most recognizable inventory models to date, was first introduced by Ford W. Harris in 1913 and has inspired a variety of fixed-quantity extensions. Since then, the field has grown exponentially to include fixed-interval models, zero-inventory models, Just-In-Time (JIT) models, and Vendor Managed Inventory (VMI), among others. On the other hand, transportation management emerged as a research area in the 1960s, after being first introduced by the military in World War II. It too has accumulated a vast catalogue of models and methods including transportation mode selection, scheduling and routing, to name a few. The integrated modelling of these two supply chain activities, however, is a more recent development.

Integrated Transportation-Inventory (ITI) models incorporate transportation and inventory decisions simultaneously. The trade-off between the related transportation and inventory costs are considered in the final decision process with the goal of minimizing the overall total cost. The development of these models has taken different forms, including models with special focus such as routing, lot sizing and transportation policy selection. Significant progress has been made in creating models more applicable to the needs of industry through inclusion of random demand, third party logistics handlers (3PLs) and complex supply chain configurations.

The objective of this literature review is to provide an overview of ITI models developed over the last two decades for various supply chain configurations. Recurring topics will be discussed, those growing in popularity will be identified and suggestions for future research will be made. In the process, the assumptions and the constraints inherent in models will be categorized and analyzed. The purpose of this review is to provide a reference resource for researchers and managers alike, enabling them to identify articles that closely relate to their own research and practice needs.

1.1. History of integrated transportation-inventory models: early years

Prior to examining ITI research over the last twenty years, a brief overview of the development of this topic in early years is presented. Transportation costs have been incorporated into inventory models for half a century, typically through a constant cost that was amalgamated with other fixed costs such as procurement. However, it was not until the 1970s that transportation costs were explicitly included in inventory models. This differentiation is important, as the explicit inclusion of transportation cost allows for the trade-offs between transportation and inventory decisions to be independently analyzed. The impact of varying lot size, delivery frequency or routing on total cost becomes more transparent. Furthermore, explicit inclusion of transportation costs creates a model that is closer to real life practices, allowing for variability in the transportation cost structure for any number of factors, including transportation weight and distance. Such advancements had led to development of models that can be customized, thus bringing theory closer to practice in this area.

It was Baumol and Vinod [1] who proposed one of the seminal ITI models. They created a model that uses a direct shipment policy, where transportation costs are variable by unit. The model incorporates inventory holding costs into a profit maximization function used to select the transportation mode. It was found that faster and more reliable

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transportation yields the best results. Das [2] extended this research by observing a normal continuous distribution for safety stock. He noted that the discrete Poisson distribution used by Baumol and Vinod [1] indicates that the mean and variance of lead time are equal, which may not be necessarily the case in many instances. The 1970s also saw the incorporation of transportation costs into lot sizing decisions. Buffa and Reynolds [3] and Langley [4] incorporated transportation considerations into the (Q,r) inventory model. Constable and Whybark [5] brought these two avenues of research together, forming a model that jointly handled lot sizing and transportation selection decisions.

The General Motors (GM) Research Laboratories and University of California paired up in the 1980s to examine ITI models with lot sizing using the EOQ inventory policy. A variety of articles were generated from this partnership [6,7,8] including a decision tool to help manage GM's global network with simultaneous consideration of transportation and inventory decisions. This was achieved through analysis of single transportation links with results generalized across the larger network. These models also considered product grouping and consolidated shipments.

ITI models with routing surfaced in the mid-80s when Bell et al. [9] presented a model for inventory routing for a single period. Federgruen and Zipkin [10] extended this model by including both inventory and vehicle routing, using decomposition techniques for solution. ITI models with routing have supported both direct shipment [11] and multi-stop shipment [12] in minimizing the long-term average cost. In the 1990s, the single period routing model was abandoned in favour of an infinite horizon model by Anily and Federgruen [13]. They later extended their original model with consideration of a two-echelon supply chain with routing from a central warehouse [14].

1.2. Previous literature reviews on transportation - inventory models

There are numerous review articles available that focus on transportation or inventory models. However, there are only a few reviews that focus on the integration of these two key supply chain activities. Those that do tend to be narrow in scope, focusing only on a specific aspect of ITI modelling, such as routing [15], global supply chains [16], green initiatives [17] and transportation mode selection [18]. We focus below on three previous review articles that take a broader perspective on ITI models.

Min and Zhou [19] were the first to tackle the ITI modelling. They provided a general overview of supply chain modelling that includes ITI models dealing with location, supplier selection, collaborative models and lot sizing. Their review stresses the importance of supply chain structure, operations and drivers. The authors suggested that the way forward is through multi-objective modelling in order to incorporate a variety of supply chain functions. The contribution of this review article was in its synthesis of previous research with a specific breakdown of decision variables and constraints.

The review article by Williams and Tokar [20] is the one that is most in line with our current review. The article serves as a catalogue for inventory models with a focus on the collaboration between inventory and other functions, including transportation and warehousing. The primary focus was on stochastic models within the subset of reorder point inventory policies. The authors stressed the importance of developing collaborative models for stochastic demand that encompass other inventory policies, as well as, lost sales instead of backorders. The authors argued that such policies and attributes to be more reflective of actual business practices. However, the decision variables in this review article exclusively relate to inventory policy. Consequently, further potential reduction of costs through transportation mode selection and routing was not considered. On the other hand, our review article extends the work of Williams and Tokar [20] by including ITI models where transportation decisions are not fixed. Furthermore, we include the special topics that only have become points of interest over the last decade, including carbon emissions reduction and forward-reverse logistics.

Bartolacci et al. [21] prepared a review article that was primarily aimed at practitioners. The article also concentrated on ITI models, emphasizing practical implementation of optimization tools for strategic, tactical and operational decisions. A main focus was on the impact that increased computing power has on modelling and what this means for the future of collaborative models, particularly for multi-echelon supply chain configurations.

The remainder of the article is organized as follows: Section 2 discusses the methodology used in searching for articles. The features and constraints inherent in the various models are provided in Section 3 along with identified trends. Section 4 discusses the main contributions of ITI articles published during the 1997–2017 period based on the model type classification the article belongs to. Finally, concluding remarks and avenues for future research are presented in Section 5.

2. Methodology used in article selection

The articles considered in this literature review were amassed using SCOPUS and Google Scholar as the search platform. Three searches with different keywords were conducted using each database for a total of six searches. The searches were restricted to the articles published over the last two decades (1997–2017). The keywords used in the three searches were:

search 1: “integrated” AND “transportation” AND “inventory”
search 2: “transportation” AND “inventory” AND “optimization”
search 3: “minimize” AND “transportation” AND “inventory”.

The initial list from the six searches resulted in 67 articles. The articles were then reviewed to ensure that they conform to the scope of our review. Those articles incorporating one or more of the following features were dropped: (i) qualitative in content, (ii) network configuration decisions, and (iii) not published in the targeted list of academic journals provided in Table 1. Since quantitative ITI modelling is our primary point of focus, qualitative articles that do not incorporate such models were excluded. Network configuration decisions involve facility location decisions and therefore fall outside the bounds of a fixed supply chain configuration. Finally, to ensure quality of the scholarly work reviewed, only those articles published in recognized journals with robust peer review process are considered. The titles of the 29 academic journals considered as potential publication venues for ITI articles are presented in Table 1.

As a result of the aforementioned filtering, the final list of ITI articles reviewed was comprised of 52 articles appearing in 15 journals out of the 29 journals list in Table 1. The distribution of articles by journal title is illustrated in Fig. 1. ITI articles have been most frequently published in the *International Journal of Production Economics* with eleven articles. The *European Journal of Operational Research* and *Transportation Part E: Logistics and Transportation Review* are also popular venues with nine articles each. These three journals account for over half of the 52 articles reviewed.

The distribution of articles by year is illustrated in Fig. 2. The peak occurred when six ITI articles were published in 2014, closely followed by five articles in 2008 and 2010. Ups and downs, as well as, a slightly increasing trend are observed in the number of publications in this area over the last two decades.

3. Features of integrated transportation-inventory models

The ITI models presented vary in terms of the topics treated and the supply chain configuration used. These models incorporate various constraints which determine their scope and potential use in practice. In terms of transportation characteristics, ITI models vary in transportation policy, cost structure, mode selection and capacity. Inventory related features of ITI models include number of products, demand

Table 1
Academic journals reviewed.

Annals of Operations Research
Computers & Industrial Engineering
Computers & Operations Research
Decision Sciences
Decision Support Systems
European Journal of Operational Research
IIE Transactions
Interfaces
International Journal of Logistics Management
International Journal of Operations and Production Management
International Journal of Physical Distribution & Logistics Management
International Journal of Production Economics
International Journal of Production Research
Journal of Business Logistics
Journal of Global Optimization
Journal of Manufacturing Systems
Journal of Operations Management
Journal of Supply Chain Management
Journal of the Operational Research Society
Management Science
Manufacturing & Service Operations Management
Naval Research Logistics
Omega
Operations Research
OR Spectrum
Production and Inventory Management Journal
Production and Operations Management
Transportation Research Part E: Logistics and Transportation Review
Transportation Science

distribution and stockouts. The abbreviations used in classifying ITI models are provided in Table 2.

3.1. Types of ITI models and supply chain configurations

The types of models covered in the articles reviewed are classified into four groups: (i) general ITI models, (ii) ITI models with lot sizing, (iii) ITI models with routing and (iv) ITI models with special topics. The last group includes models on VMI, transportation mode and policy selection, carbon emission and reverse logistics. The classification of reviewed articles is presented in terms of the following attributes: model and formulation type, methodology used, type of supply chain configuration, product specifications and transportation specifications.

Articles reviewed are discussed in Section 4 in line with the model type classification. While there is the most literature on special topics ITI models, the distribution among the categories is fairly even, apart from lot sizing, which accounts for under 20% of the articles reviewed. Furthermore, routing and special topics have both seen increased interest over the last decade, while the frequency of general models has remained steady, whereas the frequency of lot sizing models has lessened (Fig. 3). The steady publication of articles in special topics can be attributed to the overarching nature of this category. Prior to 2006, special topic articles were primarily comprised of transportation modes, while the special topics in the last decade have been more centered on environmental concerns such as carbon emissions and forward / reverse logistics.

The supply chain configurations used in ITI articles have been categorized as: (i) single-single, (ii) single-multiple, (iii) multiple-single, and (iv) multiple-multiple. The first entry indicates how many vendor locations are considered, while the second entry indicates the number of customers. For example, a single-multiple configuration indicates a single vendor serving multiple customers. These supply chain configurations are illustrated in Fig. 4. The single-single supply chain configuration appears most frequently, being used in 19 of the 52 articles (36.5%), while the single-multiple and multiple-multiple supply chain configurations each account for approximately 30%. The multiple-single supply chain configuration is by far the least studied configuration used in only two articles, both in the routing context. The prevalence of the single-single supply chain configuration is not surprising, as this configuration typically serves as a building block for more complex supply chain configurations.

3.2. Product oriented specifications and inventory assumptions

Product specifications varied by article in terms of demand distribution, stockout policy and the number of products considered (Table 3). The assumption of deterministic demand was seen in just over half of the articles reviewed. Models including only a single product were also favoured by researchers over multiple product cases. Stochastic demand models are more prevalent in general ITI models as well as the ones that consider VMI and, lately, in routing models. On the

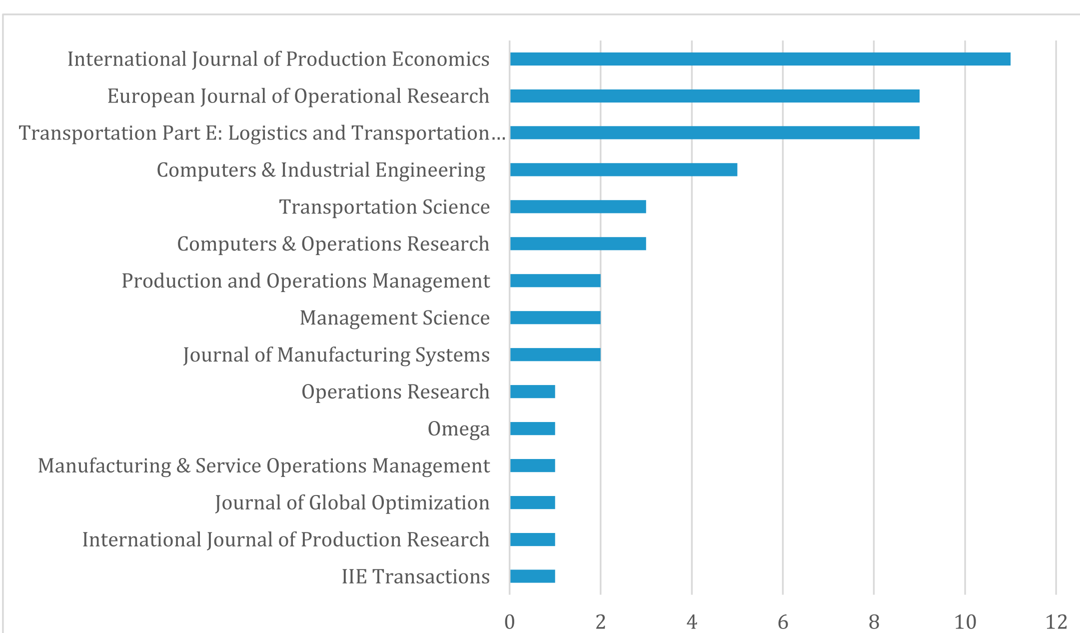

Fig. 1. Distribution of reviewed articles by journal title.

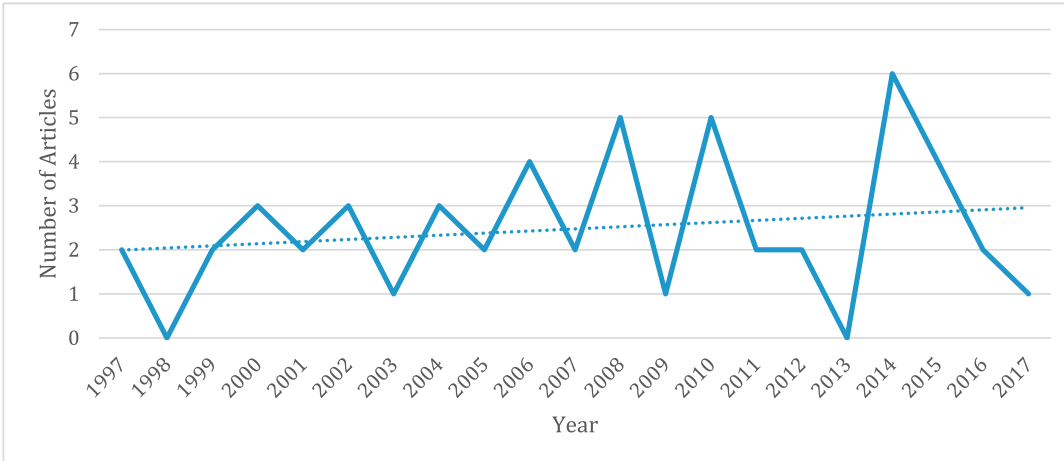

Fig. 2. Distribution of reviewed articles by year.

Table 2
Abbreviations used.

Model	**Type**	GITI : General Integrated Transportation-Inventory Model
		ITIR: Integrated Transportation-Inventory Model with Routing
		ITILS : Integrated Transportation-Inventory Model with Lot Sizing
		STITI : Special Topic Integrated Transportation-Inventory Model
	Formulation	LP : Linear Programming
		NLP : Nonlinear Programming
		IP : Integer Programming
		MIP : Mixed Integer Programming
		MDP : Markov Decision Process
Supply chain	**Configuration**	S-S : Single-Single
		S-M : Single-Multiple
		M-S : Multiple-Single
		M-M : Multiple-Multiple
Product specifications	**Product**	S : Single
		M : Multiple
	Demand	D : Deterministic
		S : Stochastic
	Backorder/Stockout	B : Backorders
		LS : Lost Sales
Transportation specifications	**Policy**	DS : Direct Shipment
		TS : Travelling Salesman
		TR: Transshipment
		CD : Crossdocking
		CL : Closed Loop
	Costs	F : Fixed
		V : Variable
		PW : Piecewise

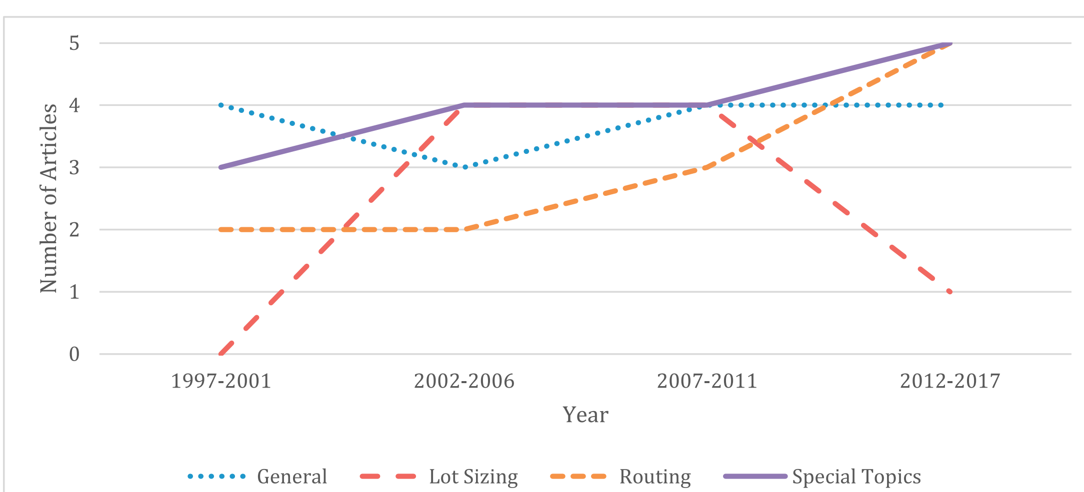

Fig. 3. Distribution of reviewed articles by model type over the years.

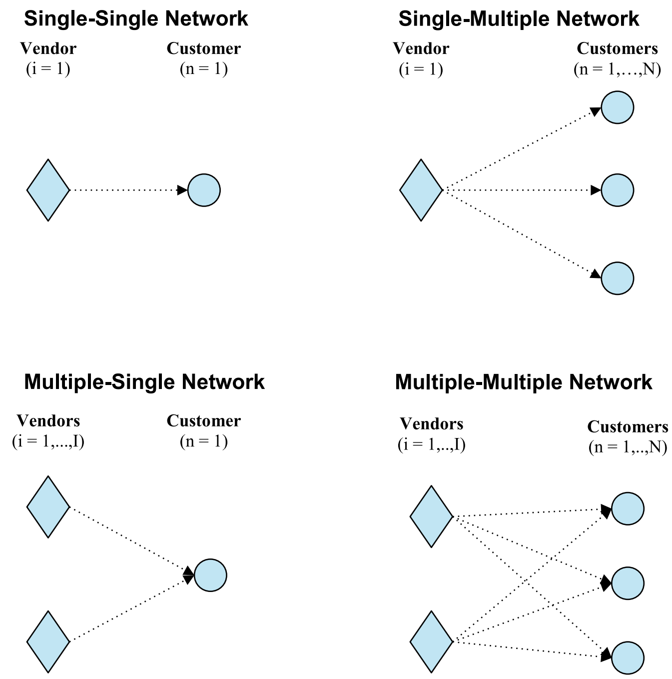

Fig. 4. Supply chain configurations used in reviewed articles.

other hand, stochastic demand is mostly absent in ITI models that consider carbon emissions.

When allowed, stockouts in ITI models are treated as backorders or as lost sales. Typically, there is a penalty associated with backorders and lost sales, while not allowing stockouts implies complete demand fulfilment. The majority of the articles did not allow stockouts. Like deterministic demand, such an assumption eases modelling and lowers computation time. Typically, uncontrollable supply disruption or high demand variability will cause backorders or lost sales. Only 14 of the articles reviewed considered backorders, whereas lost sales is considered in five articles.

3.3. Transportation features and constraints

Features and constraints related to transportation are an integral part of ITI models and have significant impact on the adaptability of individual models to various industry practices. These include the transportation policy employed, transportation cost structure and whether transportation is capacitated or not (Table 3). More than half of the articles reviewed considered capacitated transportation.

The primary transportation policies considered are direct shipment and travelling salesman. Direct shipment is the most straightforward method, as it involves a product being shipped directly from the vendor to the customer. It appears as the transportation policy in just under 60% of the articles. Furthermore, three articles considered direct shipment with postponement [22–24]). There were two studies [25,26]) where models were used to determine whether to use direct shipment or cross docking. Cross docking as the sole transportation policy was reported only once [27], whereas transshipment was used as the transportation policy in three articles [28–30]. On the other hand, travelling salesman as a transportation policy appeared relatively frequently. This is a policy that includes multiple stops along a designated route, aiming to minimize the distance travelled. A milk run transportation policy was observed in three articles [31,22,24]. This policy also entails multiple stops. However, the route is not necessarily determined by distance. Finally, a closed loop transportation policy, where vehicles carry products during the outbound and inbound routes, was studied twice, both in the context of integrated forward-reverse logistics [32,33]. In terms of alignment with industry practices, there is no one best option when selecting a transportation policy. Such policies are dependent on supply chain configuration and organizational requirements. Cross docking is an area that has been less explored in the articles reviewed, despite its popularity with large retailers and 3PLs [34].

Transportation cost structure is an important aspect of ITI modelling as the transportation cost, along with the holding cost, are the primary costs to minimize. Hence, the transportation cost structure plays a key role in determining the output decisions of the model. The transportation cost function must reliably represent the situation at hand for any useful insight to be gained from the model. In the articles reviewed, the cost structures varied in complexity from a fixed trucking cost to a multi-level piecewise function. A relatively even distribution was observed among fixed and variable cost structures. The variable transportation cost is a linear function of distance, unit and / or handling. A fixed cost structure best represents situations where shipments are delivered by full truckload (FTL), while a variable cost structure may be better suited for less-than-truckload (LTL) delivery. A combined function was also used with relative frequency, incorporating both fixed and variable aspects into the cost structure. Two studies [35,36] examined transportation mode selection, as well as selecting among fixed and variable transportation cost options. Transportation costs as a piecewise function, usually with weight breaks, were used in only approximately 10% of the articles. This cost structure is significantly more difficult to model due to its nonlinear form. However, when using a 3PL, a piecewise cost function is a much better representation of the LTL transportation rates in practice. The increase in use of these services underlines the importance of further research involving piecewise transportation cost modelling, as well as a combination of piecewise and fixed transportation costs for organizations using both LTL and FTL transportation.

4. Integrated transportation – inventory models

ITI models incorporate lot sizing, inventory routing, transportation policy and transportation mode selection decisions. These are often considered to be tactical decisions as the solutions prescribed from the models are usually for a medium-term horizon. General ITI models tend to offer more flexibility than specific-purpose models, making several key decisions simultaneously and can aid in making strategic decisions for long-term planning. This section discusses the articles reviewed and it is organized as follows: (i) general ITI models, (ii) models with lot sizing, (iii) models with routing and (iv) special topics in terms of transportation policy and mode selection, vendor managed inventory and environmental concerns.

4.1. General integrated transportation – inventory models

General ITI models consider two domains: those that focus on a single organization (unit environment) and those aimed at collaborative decision-making among two or more organizations (chain environment). In the articles reviewed, there were two prevalent supply chain configurations for single organization models: the single-multiple configuration and the multiple-multiple configuration.

The objective of a single-multiple model is to minimize the vendor's costs of inventory and transportation at a single facility while serving their customers at multiple locations either with no stock-outs or within a predetermined service level. The single-multiple configuration was explored in two general ITI models with differing transportation policies and cost structures. The cost-effectiveness of a direct shipment policy, with variable cost structure, was investigated by Barnes-Schuster and Bassok [37]. The authors constructed a total cost lower bound for a nonlinear program, investigating a single product experiencing stochastic demand. This study illustrated that direct shipment is the lowest cost transportation policy when vehicle capacity was similar to average demand. While this is useful for FTL shipments, it does not

Table 3
Classification of reviewed articles.

Year	Author	Type	Model Formulation	Methodology	Supply chain configuration	Product specifications Product	Demand	Backorder/ stockout	Transportation specifications Policy	Modes	Costs	Capacity
2006	Abdelmaguid & Dessouky	ITIR	NLP	Genetic algorithm	S-M	S	D	B	TS	1	F + V	Yes
1997	Barnes-Schuster & Bassok	GITI	NLP	Lower bound + simulation	S-M	S	S	B	DS	1	V	Yes
2004	Ben-Daya & Hariga	ITILS	NLP	Iterative algorithm	S-S	S	S	B	DS	1	F	No
2006	Berman & Wang	STITI	IP	Lagrangian relaxation + greedy heuristic	M-M	M	D	N/A	DS or CD	1	F	Yes
2015	Bertrazzi et al.	ITIR	MIP	Matheuristic	S-M	S	S	LS	MR	1	F	Yes
2014	Büyükkaramikli et al.	GITI	NLP	Simulation + heuristic	S-S	S	S	B	DS	1	F	Yes
2001	Cachon	STITI	NLP	EOQ heuristic	S-S	M	S	B	DS	1	F	Yes
2014	Carlsson et al.	STITI	LP	Robust optimization + simulation	M-M	M	D + S	N/A	TR	1	V	Yes
2000	Çetinkaya & Lee	STITI	NLP	Renewal Theoretic Model	S-M	S	S	LS	MR	1	F	Yes
2006	Çetinkaya et al	STITI	NLP	Analytical Research	S-M	S	S	LS	MR	1	F	No
2002	Chan et al.	GITI	IP	Algorithm + Linear Heuristic	S-M	S	D	N/A	CD	1	PW	No
2001	Chaouch	STITI	NLP	Optimization	S-S	S	S	B	DS	1	F	No
2006	Cochran & Ramanujam	STITI	IP	Optimization + best packing heuristic	S-S	S	D	N/A	DS	3	F	Yes
2016	Cui et al.	GITI	MIP	Lagrangian relaxation algorithm	M-M	S	S	N/A	DS	2	V	No
1997	Das & Tyagi	GITI	NLP	Optimization	M-M	S	S	N/A	DS	1	V	No
2007	Ertogral et al.	ITILS	LP	Optimization algorithm	S-S	S	D	N/A	DS	1	PW	No
1999	Fumero & Vercellis	ITIR	MIP	Lagrangian Relaxation + Decomposition	S-M	M	D	N/A	TS	1	F + V	Yes
2012	Glock	ITILS	MIP	Iterative algorithm	S-S	S	S	B	DS	1	F	No
2008	Hoque	GITI	MIP	Optimization	S-M	S	D	N/A	DS	1	F	No
2000	Hoque & Goyal	GITI	LP	Optimization algorithm	S-S	S	D	N/A	DS	1	F	Yes
2004	Huang	GITI	MIP	Optimization	S-S	S	D	N/A	DS	1	F	No
2010	Huang & Lin	ITIR	NLP	Ant colony optimization	S-M	M	S	LS	TS	1	V	Yes
2010	Hwang	ITILS	MIP	Polynomial time algorithm	S-S	S	D	B	DS	2	F + V	Yes
2014	Jha & Shanker	ITIR	MIP	Lagrangian multiplier + decomposition	S-M	S	S	B	DS	1	F + V	Yes
2010	Kang & Kim	ITILS	MIP	Two-phase heuristic + dynamic programming	S-M	S	D	N/A	TS	1	F + V	Yes
2014	Konur	STITI	LP	Local search algorithm	S-S	S	D	N/A	DS	4+	F	Yes
2014	Konur & Schaefer	STITI	IP	Optimization	S-S	S	D	N/A	DS	2	F or V	Yes
2008	Kutanoglu & Lohiya	GITI	MIP	Optimization	M-M	S	S	N/A	DS	3	V	No
2008	Lee et al	GITI	MIP	Decomposition heuristic	M-M	S	D	N/A	DS	1	V	Yes
2016	Lee et al	ITIR	IP	Meta-heuristic	S-M	S	D	N/A	TS	1	F + V	Yes
2017	Mogale et al.	GITI	MIP	Max-min ant system meta-heuristic	M-M	S	D	N/A	TR	2	F + V	Yes
2010	Musa et al.	ITIR	MIP	Ant colony optimization	M-M	M	D	N/A	DS or CD	1	V	Yes
2015	Niakan & Rahimi	ITIR	MIP	Fuzzy multi-objective optimization	M-M	M	D + S	N/A	TS	1+	F + V	Yes
2009	Pishvaee et al.	STITI	NLP	Scenario-based computations	M-M	S	S	N/A	CL	1	V	Yes
1999	Qu et al	ITIR	MIP	Decomposition with lower bound	M-S	M	S	B	TS	1	F + V	No
2008	Rieksts & Ventura	STITI	MIP	Heuristic	S-S	S	D	N/A	DS	2	F or V	Yes
2011	Rong et al.	GITI	IP	Optimization	M-M	S	D	N/A	DS	1	F	No
2014	Sadeghi et al.	STITI	MIP	Multi-objective heuristic + genetic algorithm	S-M	S	D	N/A	TS	1	V	No
2007	Salema et al	STITI	MIP	Optimization	M-M	M	S	N/A	CL	1	V	No
2011	Sancak & Salman	ITILS	IP	Optimization	S-S	M	D	LS	DS	1	F	Yes

(continued on next page)

Table 3 (*continued*)

Year	Author	Type	Model Formulation	Methodology	Supply chain Configuration	Product specifications: Product	Product specifications: Demand	Backorder/stockout	Transportation specifications: Policy	Transportation specifications: Modes	Transportation specifications: Costs	Capacity
2008	Savelsbergh & Song	ITIR	IP	Optimization algorithm	M-M	S	D	N/A	TS	1	V	Yes
2015	Schaefer et al.	STITI	NLP	Pareto Front algorithm	S-S	S	S	B	DS	2	F or V	Yes
2005	Sindhuchao et al.	ITIR	IP	Brand & price algorithm + greedy heuristic	M-S	M	D	N/A	TS	1	F + V	Yes
2012	Solyali et al.	ITIR	MIP	Robust optimization	M-M	S	D + S	N/A	TS	2	F + V	Yes
2002	Swenseth & Godfrey	STITI	NLP	Inverse function heuristic	S-S	S	D	N/A	DS	2	PW	No
2015	Tempelmeier & Bantel	GITI	NLP	Optimization	S-M	S	S	B	DS	1	F	Yes
2003	Toptal et al.	GITI	IP	Heuristic with error bounds	S-S	S	D	N/A	DS	1	PW	Yes
2005	van Norden & van de Velde	ITILS	IP	Lagrangian relaxation algorithm	S-S	M	D	N/A	DS	2	PW	Yes
2002	Yokoyama	ITILS	LP	Simulation + random search & genetic algorithms	M-M	S	S	B	DS	1	F	No
2000	Yu & Li	GITI	LP	Robust optimization	M-M	S	S	N/A	DS	1	V	No
2004	Zhao et al.	ITILS	IP	Algorithm	S-S	S	D	N/A	DS	1	F + V	Yes
2010	Zhao et al.	STITI	MDP	Markov decision process	S-M	S	D	B	TR	2	F + V	Yes

address the LTL shipments which are common in practice. An alternative shipping policy, considering the use of cross-docking with LTL shipment, was later examined by Chan et al. [27]. Using deterministic demand, they used a piecewise function with weight brackets to model transportation costs, emulating the use of a 3PL. Since cross-docking do not involve holding inventory, this transportation policy is considered to be a zero-inventory system. Despite the deterministic demand and the assumption of no stock-outs, the piecewise nature of the transportation cost structure makes this transportation policy difficult to model and solve for optimality within a reasonable time. The model was formulated as an integer programming model. Both an exact algorithm and relaxed linear heuristic were proposed. The authors showed that, using the proposed heuristic, an organization can achieve a zero-inventory system only within 33% of the optimal solution, albeit with significant savings in computation time.

A variation in the objective function was introduced in Tempelmeier and Bantel [38].For the single-multiple supply chain configuration studied, a multi-objective function is used to minimize cost, as well as, to maximize service level. Unlike previous work, the authors consider both inventory backorders and transportation backorders. A transportation backorder occurs when a product is available at the supplier, however the capacitated transportation resources are unable to deliver it within the same period due to their capacity limitations. A non-linear program was developed for optimization.

The objective of multiple-multiple ITI models is also to minimize total transportation and inventory costs. However, the addition of several vendors can result in a model that is more sensitive to uncertainty. To combat this issue, Yu and Li [39] developed a robust optimization model that is less sensitive to variability in the input data, thus better reflecting real-life scenarios. Their method required less control variables and computation time than previous models, as illustrated through two case studies, when the variables and parameters of the model are subject to noise. Yokoyama [40] also tackled a similar linear program, investigating optimal inventory and transportation quantities, through developing a random local search method and genetic algorithm. This method extended Yu and Li [39] model by considering backorders and allowing customers to be served by any distribution centre rather than just the geographically closest location.

A further extension to the aforementioned model was presented by Lee et al. [41] by examining a multi-echelon supply chain consisting of factories, warehouses, distribution centres and customers. The extended model was formulated as a mixed integer programming model and proposed a decomposition heuristic that was shown to perform within 10% of the lower bound when demand is deterministic. A similar supply chain configuration was investigated by Kutanoglu and Lohiya [42] using stochastic demand in the service parts domain. Service parts have a high cost and sporadic demand, making them difficult to model. Stockouts were allowed and monitored through a service level constraint. The model decisions included inventory quantity and transportation method. Three possible trucking options were considered, varying in speed and cost, all using a linear variable cost structure. Mixed integer programming was used to determine optimal inventory levels of spare parts for a variety of desired service levels. Finally, Cui et al. [43] examined a stochastic multiple-multiple supply chain configuration model which accounted for supplier failure. Supplier failure was incorporated into a mixed integer nonlinear program in two ways: by adding a base stock at all customers and by providing the option to receive an expedited shipment from an alternate supplier at a higher cost. A Lagrangian relaxation algorithm was developed to improve the reliability of the supply chain. While positive results were reported, these were contingent upon the infallibility of the expedited shipments.

There were two general ITI models within the multiple-multiple supply chain configuration that studied niche topics: a model on fresh food delivery and a model on the impact of centralization of inventory decisions. Fresh food delivery requires special consideration in modelling due to quality concerns. Rong et al. [44] tackled this issue by including food degradation, a function of temperature control, as a constraint in a mixed integer programming ITI model to minimize the total transportation, inventory and food waste costs. Another niche topic was studied by Das and Tyagi's [45] through inventory centralization. The authors examined a single product with a variety of differing inventory and transportation cost structures and then developed an optimization model that determines the ideal degree of inventory centralization for each scenario.

A three-echelon supply chain was investigated only once in the literature, in regards to India's grain supply chain [29]. Under this scenario, the silos which over-produced grain needed to transport the excess to central grain silos. The central grain silos would then redirect the grain to those silos which were experiencing a deficit. Two transportation modes were considered, road and rail, both of which were comprised of a fixed and variable cost components. Silos and transportation are capacitated, while stockouts were not considered. A multi-period mixed integer non-linear program was created to minimize the total cost when demand is deterministic. The model was solved using an improved max-min ant system meta-heuristic. The authors demonstrate through sensitivity analysis how their improved heuristic provides a lower total cost than the existing max-min ant system.

A collaborative ITI model minimizes the total transportation – inventory cost of a supply chain consisting of multiple organizations. Being the subject of relatively recent research, these models rely on coordination and cooperation between vendors and retailers to minimize costs. The most common structure considered is a single-single configuration with a single product. The collaborative ITI model was first investigated by Hoque and Goyal [46] under EOQ and direct shipment policies. Using deterministic demand, a linear programming model was formulated and an optimization algorithm was developed to determine production and delivery schedules. This article later served as a base case for multiple extensions presented below with varying inventory policies and transportation cost structures.

Toptal et al. [47] examined the same single-single configuration with a single product. However, transportation costs were modelled as a piecewise function of transportation capacity, rather than a fixed truck cost. A heuristic with error bounds was used to determine production and delivery schedules. A further development to Hoque and Goyal [46] original model included defective items and JIT inventory policy [48]. A linear programming model was proposed and solved. Their model relaxed the transportation capacity constraint and only considered homogeneous batch sizes. Hoque [49] later extended his original model to include multiple retailers. As well as analysing equal and unequal batches, he also relaxed the EOQ assumption of the earlier model and examined push and pull inventory policies via a mixed integer programming model. An optimization algorithm was presented. When there are multiple retailers, it was demonstrated that the best strategy to minimize inventory and transportation costs is one with unequal batch sizes, coupled with a push-pull hybrid inventory policy.

More recently, Buyukkaramikli et al. [50] revisited Hoque and Goyal [46] original model. However, they used a (Q,r) inventory policy with stochastic demand, variable lead time and backorders. A nonlinear model was developed to coordinate inventory and transportation for the case of an in-house capacitated truck fleet with a fixed cost structure. The transportation was modelled as a queuing system where the output was defined in terms of order quantity, reorder point and fleet size. Through simulation and heuristics, it was found that savings as much as 60% could be achieved through a coordinated system.

4.2. Integrated transportation - inventory models with lot sizing

In ITI models with lot sizing, the objective is to determine the optimal level of items to purchase and / or transport with the objective of minimizing inventory and transportation costs. These decisions are an integral component of optimizing the trade-off between transportation and inventory holding costs, as well as ensuring service level. Current research in ITI models with lot sizing can be divided into two categories: single product models and multiple product models.

The most prevalent ITI models with lot sizing in literature are those that examine a single product, especially within a single-single supply chain configuration, extending well-known lot sizing models to include a variety of transportation cost structures. An example of this is Zhao et al. [51], who revisited the classic EOQ model, adapting it to include a transportation cost with fixed and variable elements. An integer programming model was used and a solution algorithm was presented. Ertogal et al. [52] also used this technique, developing a linear programming model. The authors proposed an optimization algorithm to determine lot size when transportation cost is structured as a piecewise function of units shipped. A further extension of the basic lot sizing ITI model using a single-multiple configuration was proposed by Kang and Kim [53]. They proposed a two-phase heuristic and dynamic programming approach to solve a mixed integer formulation. Their model determined the optimal order delivery quantity and timing. The authors further expanded this class of ITI models using a travelling salesman transportation policy allowing trucks to deliver to multiple customers on the same trip.

Hwang [54] studied a single-item economic lot-sizing problem under deterministic demand with integrated production and transportation costs and economies of scale. The production cost is modelled by a concave function and the transportation cost by a stepwise function based on cargo capacity. To capture the economies of scale in production along with the effect of shipment consolidation in transportation, the author assumes concave / fixed-charge / nonspeculative nonstationary production costs and nonstationary / stationary stepwise transportation costs. Polynomial-time algorithm for the various cost structures was proposed.

Transportation lead time has emerged as a major issue in single product lot sizing problems as the implications on total cost associated with long or variable lead times can be significant, particularly when demand is stochastic. Variable lead time was the focus in Ben-Daya and Hariga [55], where lead time was examined as a linear function of lot size. Glock [56] extended this principle and developed an iterative algorithm to solve a nonlinear model that determines the lot size when lead time was highly variable. His model includes the possibility of crashing lead time at a cost, which proves especially efficient when demand is highly variable.

The consideration of multiple products from the same vendor further complicates ITI models with lot sizing as it requires coordination during order placement to optimize the transportation capacity. This problem has been explored in literature through a single-single supply chain configuration, using a variety of transportation methods, including direct shipment and travelling salesman. Van Norden and Van De Velde [57] developed a Lagrangian relaxation algorithm to determine lot sizes when unit transportation costs are non-decreasing by volume within a given transportation capacity. Their integer programming model also allowed for transportation spot-buying at an increased cost once the lot size exceeded the transportation capacity. The purpose of this two-pronged transportation policy approach was to simulate an environment where an organization uses a contracted 3PL handler with limited capacity and does not allow stock-outs. This was later expanded by Sancak and Salman [23] with consideration of stock-outs which were analyzed through service level. They used the basic fixed per-truck transportation cost structure, but incorporated transportation postponement to increase transportation capacity usage. Safety stock was incorporated into the lot size decisions to offset the delay in transportation. An integer linear programming model was developed and solved.

4.3. Transportation – inventory models with routing

Another special case of the ITI models involves routing. This is a subset in ITI modelling that jointly considers inventory management and vehicle routing with the objective of minimizing total cost. Current research on these models can be divided into two categories: those that consider only a single vendor and those with multiple vendors.

For a routing decision to exist, there must be multiple vendors and / or multiple customers. The single-multiple configuration was first considered using multiple products, albeit with deterministic demand and no allowance for stock-outs [58]. A routing heuristic was proposed for an existing integrated production-inventory-distribution problem. Their mixed integer programming model focused on the transportation aspect, with a cost structure that included a fixed cost plus a variable cost by unit for the outbound route and a variable cost by distance for the return route. Backorders were then incorporated into the single-multiple configuration by Abdelmaguid et al. [59], who developed a genetic algorithm focused on delivery schedule. The contribution of their nonlinear model was the allowance of partial shipment, resulting in savings in shortage costs. Their proposed algorithm offered solutions within 20% of optimality.

As to stochastic demand, a specific scenario of the multiple product problem was considered by Huang and Lin [60] for the vending machine industry. This industry is unique, as demand is only known upon arrival to fill the machine. An ant colony optimization algorithm was developed based on stock-out cost rather than the distance travelled. The proposed algorithm showed significant savings in cases where an organization has a given transportation fleet and experiences highly uncertain demand. A more encompassing stochastic routing problem, with consideration for production, inventory and transportation, was presented by Jha and Shanker [61]. Using a service level constraint to regulate backorders, they used decomposition to offer solutions for this multi-stage mixed integer programming model.

Stochastic demand was also considered by Bertrazzi et al. [31], who presented evidence that it is possible to substantially reduce costs in the case of stochastic demand over a finite horizon, as opposed to using average demand over an infinite horizon. They extended the routing framework to incorporate more accurate probability distributions over a finite horizon. A metaheuristic that considered lost sales was developed and shown to perform near-optimality. They also considered on-the-spot transportation procurement rather than an in-house fleet. This was considered to be an extension of previous work, although in practice it does not function any differently than a fixed transportation cost. More recently, a finite horizon case was studied by Lee et al. [62] with a focus on synchronization of production and delivery. They extended previous research by using a travelling salesman policy with variable cost. However, in doing so, they reverted to more simplistic product assumptions, including observing demand as deterministic and not allowing stock-outs. A comparison between their proposed synchronized integer model and independent policies showed that synchronization of production and delivery can produce significant savings.

Solyali et al. [63] presented a robust version of inventory-routing problem where a supplier distributes a single product to multiple customers facing dynamic uncertain demands over a finite discrete time horizon. The uncertainty in demand was captured using interval uncertainty with no specific probability distribution. The authors propose a branch-and-cut based exact algorithm for solving the problem. Their results show that the robust solutions obtained provide immunization against uncertainty with a slight increase in total cost compared to the nominal case, especially when the ratio of average daily demand over vehicle capacity is low. The price of robustness is found to be larger when the average daily demand over vehicle capacity ratio is high.

A multiple-single supply chain configuration has been examined in two articles in the literature, both considering multiple products. Qu et al. [64] developed a decomposition heuristic using a travelling salesman transportation policy in a stochastic setting. The mixed integer programming model examined the interaction between inventory and transportation and provided near-optimal routing policies. This model was modified by Sindhuchao et al. [65] into a pure integer model in an EOQ setting with consideration of transportation capacity. The solution was found using a lower bound and a branch and price algorithm.

Finally, the multiple-multiple supply chain configuration using ITI models with routing appeared in two articles. Using a single product, Savelsbergh and Song [66] elaborated on previous research by including the possibility of stock-outs at some vendors, requiring product pickups at different facilities prior to customer delivery. Their model also considered customers that could not be served with ‘out and back’ trips. An integer programming model was created that serves a much larger geographic region with the possibility of a route spanning over multiple days. A local search optimization algorithm was developed to determine optimal routes with no stockouts for customers. Using multiple products, Musa et al. [26] developed an ant colony optimization to determine inventory routing that minimized cost with both cross docking and direct routing transportation options. The final algorithm was shown to outperform the traditional branch and bound technique in numerical tests.

Niakan and Rahimi [67] presented a multi-objective mathematical model to address an inventory routing problem for medicinal drug distribution to healthcare facilities. The model captures the tradeoff between the total cost for drug (pharmaceutical) distribution, the satisfaction of the customer (hospital) and the total Greenhouse Gas (GHG) emissions produced in transportation over the planning horizon. The first part of objective function covers costs related to the inventory (holding and shortage) and transportation issues. The second part of objective function considers customer satisfaction as it minimizes the amount of expiration and error in demand forecasting which caused by drug shortage over the planning horizon. The third part of the objective function considers GHG emissions of the transportation vehicles. The proposed model facilitates tactical / operational-level decisions such as the set of hospitals to be visited in each period, the delivery sequence for each transportation mode, as well as the quantity of drugs delivered to each hospital in each period. To deal with uncertainty in parameters such as demand, shortage and transportation costs, the authors used a possibilistic fuzzy approach to transform the fuzzy mathematical model into an equivalent crisp model.

4.4. Special topics in transportation – inventory models

Further to the general models and models with lot sizing and routing, few special topics have been of interest in ITI modelling in the last two decades. Notable among them are transportation policy, mode selection and vendor managed inventory (VMI). More recently, environmental concerns have led to an interest in incorporating carbon emissions and reverse logistics into ITI models.

4.4.1. Transportation policy and mode selection

Transportation mode selection models are used as decision-making tools to determine the best transportation choice among several options. These models can be at strategic or tactical level depending on whether the model is developed to find out the optimal (right) transportation policy or simply the transportation mode. Transportation policy was examined by Cachon [68] in a single-single supply chain configuration with multiple products and a fixed transportation cost. An EOQ based heuristic was developed to determine the most cost-effective transportation policy among the three options: continuous review inventory with minimum quantity transportation, periodic review inventory with full service transportation and periodic review inventory with minimum quantity transportation. The heuristic determined that the continuous review with minimum quantity transportation performs best, especially when lead time is short. Berman and Wang [25] also considered selecting the best transportation policy through an integer programming model to guide decision makers between direct shipping, cross-dock shipping or a hybrid of the two. A greedy heuristic was developed to determine an upper bound coupled with a branch and bound algorithm used to refine the solution.

Transportation mode selection was examined by Sweneth and Godfrey [69] by incorporating explicit transportation costs into the EOQ model. The transportation mode options were LTL using industry practice costs represented by a piecewise function with weight breaks and FTL using variable cost by distance. Using the inverse function, a heuristic was developed to determine the best transportation mode. An important inclusion in their model was the incorporation of over-declaring. This is a popular LTL industry practice where a vendor claims a delivery to weigh more than it does, to capitalize on a lower per pound transportation cost. Total cost minimization through selection among various packing materials and container sizes was examined by Cochran and Ramanujam [70]. An integer programming model was developed and its functionality was illustrated through a case study for the electronics industry. The authors also created a decision tool to decide the best option among the 3PL providers. Transportation mode selection was also examined in terms of its relation to inventory by Rieksts and Ventura [36]. Considering multiple transportation modes, they developed a mixed integer programming model and presented an algorithm to determine inventory policies over both finite and infinite planning horizons. Transportation modes used included FTL with a fixed cost, LTL with a variable cost per unit and a mix of both. The findings indicated that a decrease in costs of up to 24% can be experienced by having both FTL and LTL options simultaneously.

4.4.2. Vendor managed inventory

Vendor Managed Inventory (VMI) is a business model where the vendor is responsible for monitoring and maintaining inventory at the retailer. This model has gained popularity as it can reduce inventory in the supply chain, lessen the bullwhip effect and reduce stock-outs. However, it also requires a higher level of coordination and collaboration among the supply chain members.

With the burden of inventory and transportation costs placed on the supplier, Chaouch [71] examined the case where the stockout cost also being assumed by the supplier. A single-single supply chain configuration was examined where the retailer applied pressure on the supplier to increase demand responsiveness. Viewing demand and lead time as stochastic, a nonlinear model was developed to determine the optimal trade-off between inventory, transportation and stock-out costs. Other researchers investigated the single-multiple supply chain. A nonlinear programming model for synchronizing inventory and transportation in VMI supply chains was presented by Cetinkaya and Lee [22]. Their original contribution was the use of delayed transportation in order to capitalize on consolidated shipment. The authors developed a renewal theoretic model to determine dispatch quantities and frequencies. Their model was later extended by Cetinkaya et al. [24] by examining total cost in VMI systems with both quantity-based dispatch and time-based dispatch policies. It was determined that quantity-based dispatch offers the lowest cost, but it also results in a lower service level. To remedy this, a hybrid policy was proposed, where a timeframe constraint was placed on a minimum dispatch quantity policy. More recently, a fully integrated VMI model that accounts for lot size, replenishment frequency and routing have been presented by Sadeghi et al. [72]. On the production front, redundancy allocation was considered to maximize system reliability. A multi-objective mixed integer programming model was developed and two genetic algorithms were presented to solve this complex case.

4.4.3. Environmental concerns

An increase environmental consciousness has made a significant impact on supply chain decisions in recent years mainly through the study of carbon emissions and reverse logistics. Researchers have incorporated this trend into ITI models largely through constraints in their models. However, the objective of the ITI model still remains the minimization of transportation and inventory costs.

Reverse logistics is the process of moving products upstream through the supply chain for reuse or proper disposal. Previous research on ITI with reverse logistics had been primarily case based. This issue was addressed by Salema et al. [33] who proposed a generalized model for wider use. Their mixed integer programming model included multiple products experiencing stochastic demand. An optimization method was developed using a closed loop transportation policy and its use was demonstrated through a case study. This research was extended by Pishavee et al. [32] with the inclusion of an integrated forward-reverse transportation network. Their nonlinear model was validated through scenario-based computations and proved to be less sensitive to demand fluctuations than previous models.

Carbon emissions are a byproduct of burning fossil fuels and primarily configured into supply chains through transportation. Organizations are encouraged to reduce their carbon emissions through incentives, regulation and taxation. The most widely known deterrent for excess carbon emissions for organizations is government cap and trade policies. Konur [73] developed a heuristic search method to solve an ITI problem with carbon caps. The linear model considers various truck sizes, each with a unique fixed cost and carbon profile. Emissions are measured for inventory holding and order placement, in addition to transportation activities. The model determined that, as the maximum amount of carbon emissions allowed by the constraints becomes smaller, suppliers choose to utilize a variety of truck sizes rather than making fewer shipments. The model was extended by Konur and Schafer [35] by considering three emission policies: (i) cap and trade, (ii) cap and offset and (iii) carbon taxing. The integer programming model was further extended with the inclusion both LTL and FTL shipments. To serve as a guide to policy making for managers, multiple scenarios were optimized, differentiated by transport preference and applicable carbon regulations.

Schaefer and Konur [74] also considered the case of carbon emissions under stochastic demand. Two bi-objective nonlinear programming models were developed that minimized emissions and cost. A Pareto frontier was determined for both FTL and LTL transportation. The findings can be used by managers to select a (Q,r) inventory policy that suits their needs, in line with their desired emission reduction and monetary investment levels. A particularly interesting finding was that both cost and emissions increase with lead time and demand variability. This suggests that a crucial stepping stone for managers in reducing emissions is through investments in reduction of variability in lead time and demand.

VMI operated supply chains with multiple customers are studied in two case based articles. A single coal supplier shipping coal first by rail and then by water carrier to the four subsidiaries of a petrochemical products company located along a river in China was the supply chain configuration used in Zhao et al. [30]. The proposed supply network involves the establishment of a central warehouse at the port of coal transshipment, the warehouse being responsible for ordering and distribution decisions. The demand from the four subsidiaries were consolidated and met on a JIT basis from the central warehouse, which also kept the common safety stock for the four subsidiaries. A Markov Decision Process (MDP) was developed to model the ordering and distribution decisions. Modified Policy Iteration (MPI) algorithms with action elimination procedures were used to obtain the approximate optimal action for each state. The findings indicate that the integrated ordering and distribution decisions made at the central warehouse results in substantial savings in inventory and transportation costs as a result of increased economies of scale.

Another case study, this time for a pulp producer with production mills in Sweden and Norway, was reported in Carlsson et al. [28]. The VMI based distribution planning and inventory management were studied in the context of a multiple-multiple supply chain configuration. Three cases were studied for the given problem with varying case attribute values in terms of number of mills, distribution terminals throughout Europe, products, customers and transportation modes. Three solution methods were used for the linear programming model formulated. These methods were: (i) robust optimization method developed with sequential decision making in subsequent planning periods, (ii) deterministic optimization method with varying safety stock levels and (iii) oracle method where all information was provided from the start to solve one deterministic problem. The results point out to the superiority of the robust optimization approach in reducing inventory levels at the distribution terminals and providing a good basis for the actual use of the multiple transportation modes available.

5. Avenues for future research

In this literature review, articles published over the last two decades on ITI models within a defined supply chain configuration have been classified and surveyed. The primary areas studied in recent ITI literature are general models, lot sizing, routing, transportation policy and mode selection, VMI and environmental concerns. Our review reveals that general models and routing models have made the most advancement in terms of offering solution techniques to problems that are most closely related to industry practices. In terms of coverage, the topic of environmental concerns, in particular carbon emissions, has seen the largest interest and growth in recent years.

There are several key avenues for future research. While specific future research areas are presented below by ITI model type, it should be noted that all of these areas can benefit from enriching the supply chain configuration, product characteristics and transportation characteristics. The inclusion of multiple retailers into models will help align models with industry practices, as suppliers commonly serve many locations. This same reasoning holds true for product specifications where models should be extended to include multiple products, as well as stochastic demand and stockouts. Finally, many models continue to assume direct shipment with fixed transportation costs. In order to be able to cover a variety of industry practices and organizational policies, ITI models need to incorporate more complex transportation policies including milk run deliveries and cross docking. The rise in LTL shipment and use of 3PLs also increase the need to use a piecewise transportation cost structure. Following is a discussion on future research areas by ITI model type.

- General integrated transportation – inventory models

Future research in general ITI models includes the further investigation of stochastic demand, lost sales and more complex transportation policies and cost structures. The incorporation of stochastic demand into a single-multiple configuration, coupled with consideration for transportation policies other than direct shipment, is a fertile research area. Furthermore, multiple products and a variable transportation cost structure can also be considered, as they are more reflective of everyday business practices. The emergence of zero-waste grocery stores in Europe and North America also makes food degradation models an interesting avenue for future research.

- Integrated transportation – inventory models with lot sizing

There are several areas within ITI models with multiple product lot sizing that have yet to be explored. In order to have more realistic models that better reflect industry needs, researchers may like to consider stochastic demand, single-multiple configurations and variable transportation rates.

- Integrated transportation – inventory models with routing

The initial articles reviewed in routing literature considered multiple products, which is atypical. However, in terms of demand, there were no studies that considered stochastic demand in the multiple-multiple supply chain configuration setting. Further research opportunities exist in routing models in terms of incorporating cross-docking transportation policies and piecewise transportation cost structures into these models.

- Special topics in integrated transportation – inventory models

There are research gaps in ITI models with respect to transportation mode and policy selection. Future research on transportation policy selection could include more cross-docking and travelling salesman models, as well as variable and piecewise cost structures. One area available for further exploration in transportation mode selection is the incorporation of more multi-modal transportation in ITI modelling. In the VMI area, consideration of multiple products and a variable or a piecewise transportation cost structure in modelling would enrich the current research efforts.

Carbon emission considerations in supply chain modelling is a topic of recent interest and seems to have a significant potential for future research. Supply chains configurations considered in the articles reviewed on carbon emissions have been a single-single configuration with a single product and a direct shipping transportation policy. Since transportation is a key contributor to emissions, more complex (and thus more real life) transportation policies need to be considered. The single-multiple configuration with travelling salesman transportation policy would be one such worthy combination to study. Furthermore, transportation costs need to be represented as a piecewise function with weight brackets, as this cost structure is widely used in practice for LTL shipments. Finally, to have the largest impact on environmental sustainability, carbon emissions should be factored into integrated models that include the carbon emitting production enterprise as one of the supply chain stakeholders.

Declarations of interest

None.

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Supplementary materials

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