A systematic literature review of the design of intermodal freight transportation networks addressing location-allocation decisions

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Abstract: This systematic literature review focuses on planning models jointly addressing location and allocation decisions related to the design of intermodal freight transportation networks. Since this body of literature is evolving quickly, a methodology based on a linked two-stage analysis is proposed. The first stage analyses recent surveys to establish the guidelines and criteria that enable the subsequent systematic review. Then, the review concentrates on analysing contributions to the current state of the art on intermodal freight transportation from two close, yet different research streams: transportation networks and supply chain networks. Key features identified in the first stage such as: 1) the research problem's characteristics; 2) the intermodal networks design's particularities; 3) proposed solution techniques, among others, are used to classify and analyse the different contributions. The review identifies current trends, emerging topics and some issues that merit being researched. [Received: 4 May 2019; Revised: 12 December 2019; Accepted: 1 February 2020]

Keywords: systematic literature review; SLR; intermodal facilities; network design; location-allocation problem; intermodal freight transport; mathematical programming; modelling; optimisation techniques.

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1 Introduction

Facility location-allocation problems aim to decide:

1 the best locations for facilities/nodes that offer the best service

2 allocating the flow between pairs of facilities/nodes to satisfy demand, generally minimising the total costs (Cooper, 1963; Ghaffari-Nasab et al., 2015).

Location decisions focus on the strategic level and deal with the optimal physical infrastructure of the facilities' network (Crainic and Kim, 2007). Allocation decisions focus on the tactical level and deal with services, principally by the optimal use of the facilities based on the services offered, links, and transport modes (SteadieSeifi et al., 2014). Including the transport mode decisions in this type of problem can generate a competitive advantage for the supply chain through the efficient use of transportation networks (Alenezi and Darwish, 2014) and the integration of the decision-making process (Govindan et al., 2017).

In the intermodal facility location-allocation (IFLA) problems, optimal location of facilities to perform the transhipment of the freight, and other activities such as consolidation or storage are required (Sörensen et al., 2012). Likewise, it can be necessary to locate transport resources or enable links for allocating the flow over the facilities network (Bhattacharya et al., 2014). It is important to clarify that, if the allocation is affected by the location decisions, and location is affected by the allocation decisions, then the problem is related to the network design (Alumur and Kara, 2008) and might imply operational decisions such as flow routing, freight loading and unloading, crane schedule, or even crossdocking (Garcia-Sabater et al., 2013). Nevertheless, in this article, we focus on the combined location-allocation and transport mode decisions that influence network design mainly when allocation is not trivial.

Figure 1 proposes a representation of the IFLA decisions. Given the sets of origins $i \in I$ and destinations $j \in J$ nodes, we must decide where the intermodal facilities $k \in K$ will be used or 'located', as well as the allocation of services (arcs) allowing to connect:

1 nodes of sets I and J directly

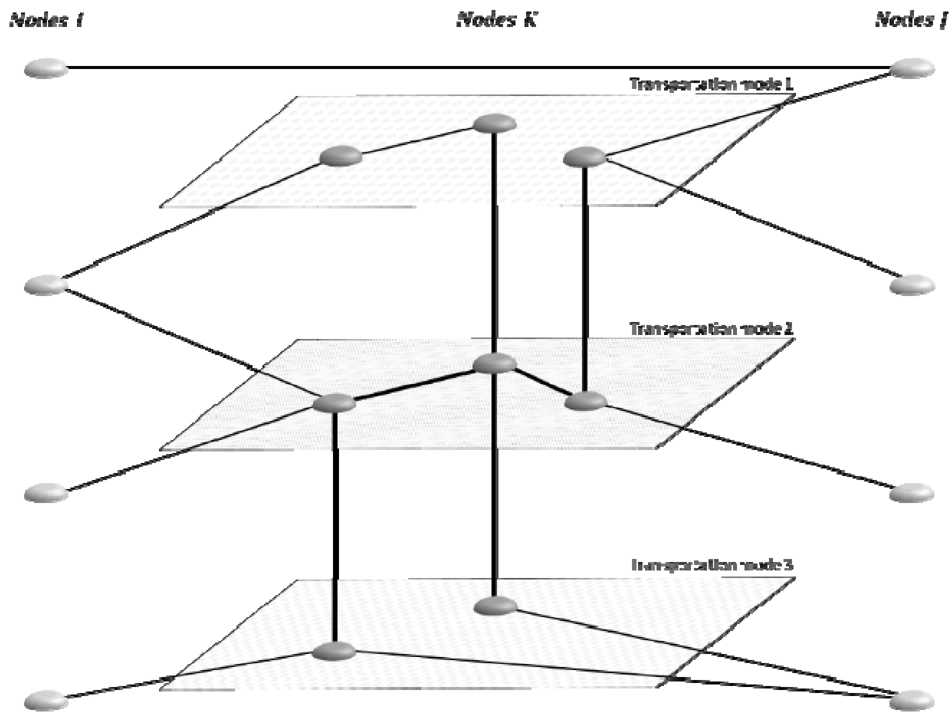
2 nodes of set I to intermodal facilities in K

3 intermodal facilities K to nodes of set J

4 intermodal facilities between them by a given transportation mode.

Each intermodal facility k can transfer freight between two or more different transportation modes, and has other attributes such as a given capacity. Further, the capacity or its expansion can be other complementary decisions (Lin et al., 2019).

Figure 1 IFLA decisions



Operations research is an important tool to assess both planning and execution in the freight transport. In particular, mathematical programming techniques are well suited to handle the level of accuracy required for the solutions and the complexity of the problems (Arabani and Farahani, 2012). Caris et al. (2014) state that combining the intermodal transport's decisions with the location-allocation decisions leads to interesting opportunities to optimise freight transport problems.

The aim of this systematic literature review (SLR) is to study how IFLA problems have been addressed using mathematical programming as the modelling technique. Specifically, we intend to investigate:

1 what the main characteristics of this type of problem are

2 what aspects are considered when combining decision-making into the network design

3 which mathematical programming techniques are being used

4 which emerging topics can be identified as potential future research avenues.

This SLR differs from earlier reviews in that it proposes a novel analytical classification for IFLA literature that enables a deeper understanding, fosters the creation of differentiating knowledge, and allows the identification of future research lines by using a linked two-stage methodology. Indeed, this SLR is relevant as it distinguishes the dichotomy on problems related to freight transportation between two close, yet different, trending research streams that correspond to two different perspectives, transport networks design and supply chain networks, and so offers a parallel analysis.

This paper is organised as follows: Section 2 describes the linked two-stage methodology process applied to perform the review. Section 3 presents the results of the first stage, where we have explicitly gone through published reviews closely related to intermodal freight transport and mathematical programming techniques. Section 4 explains the second step, which consists in a SLR, and that allowed us to identify four axes of discussion. Sections 5 to 8 are devoted to the analysis of the papers. Section 9 proposes promising research lines that emerge from the SLR and Section 10 presents the final considerations.

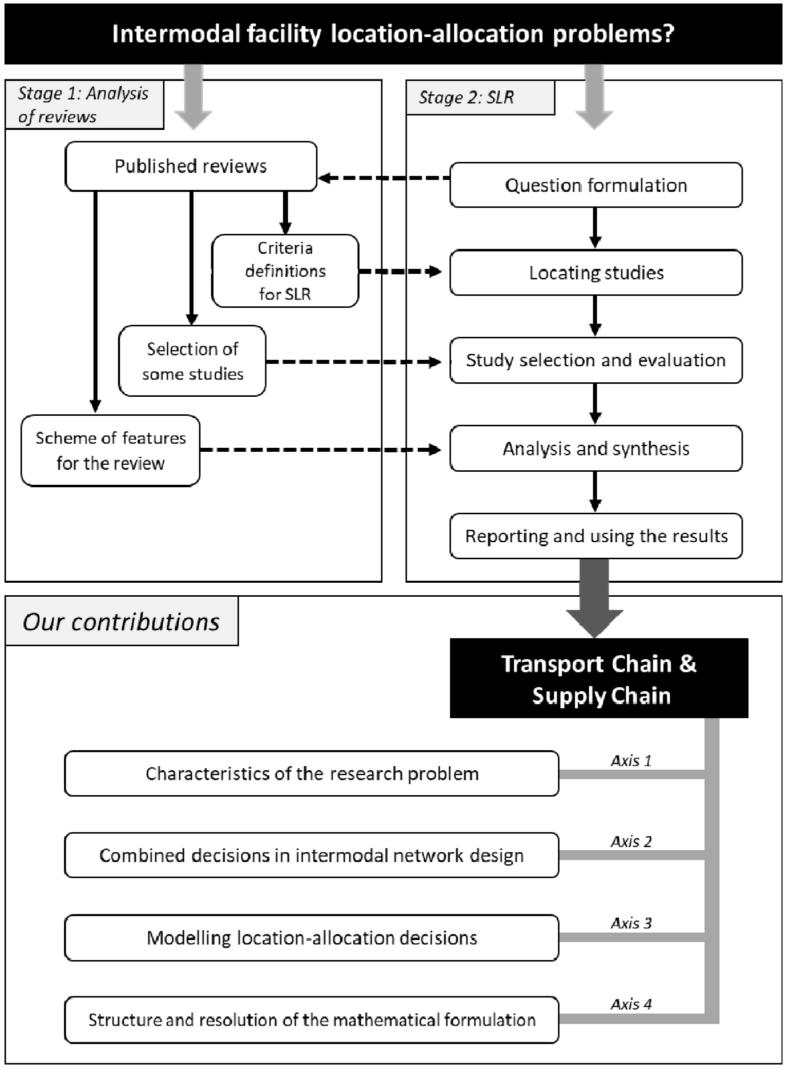
2 A two-stage methodology to perform a literature review

Freight transportation has been a research topic of growing interest, particularly since the 1990s (Agamez-Arias and Moyano-Fuentes, 2017) but the explicit modelling of transportation modes and its consideration in the design and execution of transportation networks only began to formalise at the end the 2000s. As a consequence, several works presenting the state of the art and analysing the research done so far on the topic appeared in the early 2010s. Since then, the number of works dealing with intermodal freight transportation has grown very quickly and the bounds of the research field have progressively spanned out, thus justifying the need for a systematic review to assess our research questions.

Therefore, we decided to perform a two-stage review that is depicted in Figure 2. The first stage aimed to consolidate a set of review papers relating to intermodal transport and mathematical programming. It was built according to their publication in highly reputable journals. The analysis of these papers allowed us to develop a theoretical framework that applied to guide the analysis of the SLR's and served to prevent possible pitfalls during the second stage. Section 3 presents these points in detail. Then, an SLR was performed in second stage. SLR was elected as it has been shown to be the right approach to perform a replicable literature review (Denyer and Tranfield, 2009). In Section 4 the usual steps to perform SLR are applied. The set of analysed papers comprises 16 references published between 2012 and 2017.

The findings of the analysis of IFLA problems are structured and discussed. Each of the references is positioned and their contributions are classified with respect to the four axes and 25 selected features. Furthermore, since the literature's dichotomy on problems related to freight transportation between transport networks design and supply chain becomes more and more evident, our analysis and discussion distinguish those two close, yet different trending research streams so offers a parallel analysis.

Figure 2 Linked two-stage review process



3 Stage 1 – analysis of reviews in intermodal transport and mathematical programming

The first stage of our methodology seeks to define the guidelines that align the SLR of the second stage. We are interested in papers that model intermodal transport using mathematical programming. Reviews might be classified in two large areas according to their perspective: transportation networks and supply chain networks. They must consider operational research methods to analyse a problem that includes intermodal transport.

From a transportation network's perspective, Bontekoning et al. (2004) proposed a research agenda on topics such as terminal network design. Macharis and Bontekoning (2004) analysed how to apply some of the OR tools according to the operator type (network, terminal, intermodal and drayage) but also taking into account different planning levels (strategic, tactical and operational). Leaning on this classification Caris et al. (2008) and SteadieSeifi et al. (2014) updated the previous contributions, especially with problems related with terminal design, terminal network, network flow planning, service network design among others.

The development of dynamic models and the environmental concern led to the identification of information technologies (IT) and policy support as new research lines. Caris et al. (2013) acknowledged these emergent contributions, and performed a deeper analysis on those related with terminal network design and intermodal service network design. Additionally, Caris et al. (2014) focused on contributions related with inland waterway transport. Finally, Agamez-Arias and Moyano-Fuentes (2017) identified new research lines related to the basic principles of intermodal transportation, its economic efficiency, modelling of vehicle planning and others.

From a supply chain perspective, customer satisfaction and material flows not only impact procurement, production and inventory decisions, but also on transportation decisions, distribution channels and arrangements with carriers and other actors of interest for the supply chain (Felea and Albăstroiu, 2013). Concerning environmental issues, the classification proposed by Dekker et al. (2012) analysed their integration in mathematical models, while Lam and Gu (2013) highlight the need to design and develop sustainable intermodal networks to optimise the flow of containers and to include the port hinterland in the network. On the other hand, Rožić et al. (2016) pointed out that consideration should be given to the incorporation of inland intermodal terminals.

Altogether, the ten documents mentioned above review more than 500 papers. However, it is worth noting that not all of them refer explicitly to or restrict themselves to IFLA problems. In fact, other classifications were considered but not incorporated to this research because they do not fully address our review's objective. It is worthwhile noting that the different research objectives lead to consider a large diversity of aspects. The analysis of these aspects was at the origin of the key features identified in the SLR. Moreover, the analysis led us to four main observations that were used as guidelines in the second stage. These observations are:

a Mathematical programming techniques have confirmed a great success dealing with intermodal transport, but there's still a great potential to explore IFLA problems.

b Caris et al. (2013) identified the first two papers related to location-allocation planning of intermodal facilities in 2012. We will therefore consider these papers and the year 2012 as limiters of locating the studies for our SLR's.

c IFLA problems should not only be addressed from the perspective of transport network design, but also from that of the supply chain network design. This expansion has enabled the broadening of the research's sphere to include business and planning topics.

d Although it is not the first objective of this SLR, it will be worthwhile to track emerging concepts related to sustainability, geographic area of study, territorial connectivity and accessibility, together with capturing uncertainty.

4 Stage 2 – SLR

This section describes the first four steps of the procedure executed to perform the SLR as they have been illustrated in Figure 2. In step 1 we have formulated the four following research questions related to intermodal transport: what are the main characteristics of the IFLA problem? Which features are considered for this decision-making process? Which mathematical programming techniques are being used? Which emerging aspects can be identified as future research lines?

The WOS and Scopus scientific databases were chosen as the search engines to locate the papers in step 2. The keywords initially defined were: 'intermodal transport', 'intermodal freight transport', 'location-allocation problem', 'network design', 'intermodal network design' and 'mathematical programming'. Furthermore, according to the findings in the first stage, two new keywords were added: 'integrated planning' and 'supply chain'. The area of research was not limited and the last two led to results related to the areas of economics and business, planning and development, which broadened the initial perspective skewed toward the areas of transport and operations research.

Search strategies were two-fold. A basic search with the use of Boolean operators to combine keywords and create search strings. The term 'transport' was truncated to allow words as 'transportation'. Moreover, according to SteadieSeifi et al. (2014) and Agamez-Arias and Moyano-Fuentes (2017), the word 'intermodal' was deployed to synonyms like 'intermodal' with 'multimodal', 'synchro-modal' and 'co-modal' to represent the different meanings of 'intermodal' found in the literature. Then, the snowball technique was used in the search for the cited reference to broaden the collection of papers. Finally, we decided to include the models presented by Ishfaq and Sox (2012) and Zhang et al. (2013).

Several filters were therefore applied to select and evaluate the papers in step 3. The first looked at the title and ensured that both the title and the abstract were connected with the formulated questions. Abstracts of the papers were independently read by the researchers and the results pooled their relevance and alignment with the research questions. If there was any doubt, the introduction and conclusions of the paper were read. This resulted in a high level of agreement among researchers. The second allowed to check that the problems described in each of the papers require strategic decisions to be taken on location, and tactical decisions on allocation and intermodal transport. The last filter confirmed that mathematical programming techniques were used as the main methodology to tackle the problem. The type of papers selected was peer-reviewed articles published from 2012 to 2017. Excluded documents considered conference proceedings, reports, books, book chapters, and theses/dissertations. These criteria enabled 16 references to be selected for subsequent analysis and synthesis.

In step 4 we deemed it suitable to analyse and synthesise each of the papers by identifying 25 key features. The selection of the names for the features was mainly founded on the framework presented by Bravo and Vidal (2013), although modified to allow the introduction of additional considerations. These key features were grouped into following four main axes of discussion:

1 the research problem characteristics

2 the intermodal networks' design

3 the components, variables, and parameters that are key to integrate location, allocation, and transport mode selection decisions

4 the model structure and the proposed solution techniques.

Each of the authors conducted the reference analysis and synthesis process and these were subsequently combined. Table 1 shows the proposed key features grouped by axis of discussion. The letters attached to each of the options of the key feature are used later in the tables that analyses the papers.

As the final step of the SLR, a report that summarises and uses the results obtained is to be stated. For the sake of clarity, the analysis of each axes of discussion, the perspectives of transport networks and supply chain networks are differentiated.

Table 1 Key features considered to define studies on location-allocation of intermodal facilities

Features		*Description*	
Characteristics of the research problem			
1	Network	Transport chain network (TCN)/supply chain network (SCN)	
2	Actors	TCN:	SCN:
		Intermodal transport operator (ITO)	Suppliers (S)
		Operator of intermodal facilities (OIF)	Manufacturers (M)
		Government entities (GE)	Distribution centre (DC)
			Retail outlets (RO)
			Intermodal logistics facilities (ILF)
3	Actors by type	Single (U), multiple (M)	
4	Type of flow	Directed procurement flows (DPF)	Directed flows along the network (DAN)
		Directed distribution flows (DDF)	Flows of origin-destination pairs (O-D)
5	Intermodal focus	Before the intermodal facility (BIF)	Between intermodal facility (EIF)
		After the intermodal facility (AIF)	Along the whole network (AWN)
6	Transport modes	Road-air (R-A)	Road-rail-river (R-R-R)
		Road-rail (R-R)	Road-rail-maritime-pipelines (R-R-M-P)
		Road-rail-air (R-R-A)	Road-rail-river-pipelines (R-R-R-P)
		Road-rail-maritime (R-R-M)	
7	Sector	Agricultural (A)	Mining and energy (ME)
		Container (C)	Parcels services (PS)

Table 1 Key features considered to define studies on location-allocation of intermodal facilities (continued)

Features		*Description*	
Characteristics of the research problem			
8	Product	Biomass (B)	Parcels (P)
		Biomass and ethanol (BE)	Soya (S)
		Gasoline, diesel and aviation fuel (GDF)	Single (U)
		Oil derivatives (OD)	Multiple (M)
9	Geographic area	Belgium, Brazil, Germany, Holland, Portugal, South Korea, USA, Turkey	
Combined decisions in intermodal network design			
10	Facilities	Depots (D)	Logistic integration centre (LIC)
		Distribution centre (DC)	Manufacture (M)
		Hub (H)	Transitory intermodal points (TIP)
		Intermodal terminal (IT)	Transport resources (TR)
11	Capacity	Yes (Y), no (N)	
12	Installation space	Discrete (D), discrete base network (DN)	
13	Logistics services	Classification (F)	Production (P)
		Consolidation (C)	Support services (S)
		Deconsolidation (D)	Transhipment (T)
		Inventory management (IM)	Warehousing (W)
14	Type of allocation	Single (U), multiple (M)	
15	Allocation attributes	Distances (D)	Speeds (S)
		Greenhouse gas emissions (X)	Vehicle capacity or freight unit (V)
		Inventories (I)	Transhipment costs and transport costs (C)
		Times (T)	
Modelling location-allocation decisions			
16	Network decisions	Facility location (A)	Allocation (E)
		Facility location with capacity (B)	Allocation between facilities (F)
		Facility location and operations (C)	Allocation and transport mode (G)
		Facility location and transport modes (D)	Amount of product per link (H)
17	Demand	Certainty (C), uncertainty (U)	

Table 1 Key features considered to define studies on location-allocation of intermodal facilities (continued)

Features		Description	
Modelling location-allocation decisions			
18	Costs	Closing costs of the facility (A)	Operational costs between facilities (G)
		Costs of greenhouse gas emissions (B)	Operational costs in the facility (H)
		Establishment costs of the facility (C)	Storage costs (I)
		External costs (D)	Time-related costs (J)
		Fixed costs in the facility (E)	Transportation costs (K)
		Link expansion costs (F)	
19	Times	Operational time in the facility (L)	Transport operational time (N)
		Shipping service time (M)	Wait time (O)
Structure and resolution of the mathematical formulation			
20	Optimisation type	Minimise (min), maximise (max)	
21	Objective function	Mono-objective (UO), multi-objective (MO), multi-objective multi-criteria (MM)	
22	Limitations	Greenhouse gases emission (A)	Shipping service time (E)
		Facility capacity (B)	Transport operational time (F)
		Inventories (C)	Common limitations (G)
		Investment budget (D)	
23	Periods	Single (U), multiple (M)	
24	Mathematical programming model MP type	Integer linear programming (ILP)	Mixed integer nonlinear programming (MINLP)
		Mixed integer linear programming (MILP)	Mixed integer programming (MIP)
25	Resolution procedure	Due to the particularity in phases and relaxation procedures (A), programming techniques (B) and IT tools (C) are shown directly in Table 5	

5 Characteristics of the research problem

To establish the characteristics of the research problems of IFLA planning, it is necessary to detail the features that describe the intermodal network to be designed.

The *network* feature provides a contextualisation and a definition of the actors involved. *Actors* are the decision makers, and can differ depending on the type of network. *Actors by type* provides a vision of integration, collaboration, and alignment of company objectives throughout the network. *Type of flow* represents the direction of freight traffic in the network links. *Intermodal focus* indicates the proportion of the designed network that considers intermodal flows and the installed infrastructure. *Transport modes* specifies the modes considered in the intermodal focus. *Sector* is related to the economic environment that the product represents. *Product* concerns the type of freight that is moved along the network, and *geographic area* refers to the country for which the intermodal network has been designed. Table 2 shows the characteristics of the research problems described in each of the papers considered in this SLR.

5.1 Transport networks

In general, works adopting the transport network's perspective do not specify whether the actors that make up the network are involved or the number of actors. However, it is possible to deduce the involvement of intermodal transport operators and intermodal terminal operators. The drayage operators can also be distinguished in cases involving direct dispatches with partial/full or smaller size freight. Apart from the first two mentioned operators, Zhang et al. (2015) exceptionally refer to governmental bodies being included along with other decision-making actors. They associate to each decision maker an objective in the model. Then, a hierarchical structure is assumed where the actors' objectives are subjected to those of the government.

Transport flows have mostly been modelled by origin-destination pairs in which each node in the network is considered both a point of origin and a destination. However, in some cases flows are orientated to study, for example, the export potential for a given product and region, as it is the case in Amaral et al. (2012) and Guimarães et al. (2017). Also, directed flows between origins and destinations are considered when specific delivery times need to be satisfied, as proposed by Rothenbächera et al. (2016).

The transfer of freight between modes has been considered according to three different perspectives. In the first one, the focus is on the installed intermodal infrastructure, and therefore the goal is to encouraging intermodal activity at specific locations. An example of this can be found in Guimarães et al. (2017). In the second perspective, adopted by Alumur et al. (2012) and Ishfaq and Sox (2012), the focus is on the flow between intermodal infrastructure, and the goal is to maximise the effects of economies of scale by attracting and consolidating freight. The third perspective presents the coexistence of different transportation mode options for the same link. The speed with which the transport vehicle moves, the link capacity, and even greenhouse gas emissions – as stated by Kim et al. (2013) – restrict the choice of mode and, in the final instance, node allocations. In addition, Santos et al. (2015), Rothenbächer et al. (2016) and Guimarães et al. (2017) envisage direct freight dispatches from the offer point to the demand point in parallel with the proposed intermodal focus.

In general, road and rail transport modes are the basis for intermodal network design in the transport chain. The inclusion of air transportation in the network is restricted to some particular sectors and products. River transportation depends on the geomorphological features of the zone being affected. It is surprising to state that, despite the importance of maritime transport for freight in the world – a transport mode that represents over 75% of volume worldwide (UNCTAD, 2017) – it is not considered to be an intermodal option for most of the intermodal networks being designed. Nonetheless, its use is assumed between specific geographic points and transport times and costs are included for availability of the products at maritime ports. The outer limits of the studied network designs are the intraregional and intra-continental levels. The reasons given to justify this decision might lie, on the one hand, in the complexity of integrating decisions that consider the maritime transport mode and the design of long-distance intercontinental chains and, on the other hand, in the need to develop inland networks that enhance the investments made to increase capacity at maritime ports (Zhang et al., 2013).

Although the freight transported in these networks is primarily containerised – comprising one or several products, based on the strong influence of local development and international trade in Brazil, Amaral et al. (2012) and Guimarães et al. (2017) focused on modelling a network subject to agricultural sector flows. Meanwhile, in the expectation of responding to combined location and allocation decision-making for a single actor, Alumur et al. (2012) analysed the parcel service sector with the transport of small packages.

Finally, it can be deduced that the socio-geographic context influences the orientation of the studies. Studies of IFLA in countries such as Germany, Belgium, South Korea, the USA, Holland and Turkey are aimed at improving the efficiency of the service provided, either by optimising existing infrastructure or by restructuring the network in line with the infrastructure required. In contrast, in countries like Brazil, the aim is to assess different intermodal options that highlight the need for investment with a view of integrating and expanding transportation networks in the different available modes.

5.2 Supply chain networks

The actors involved in networks designed under the concept of the supply chain include suppliers, manufacturers, distribution centres and retail outlets, although some of the actors identified in the case of transport networks may also be considered. The purpose of the studies would be to allocate the flow to existing logistic intermodal infrastructure, as in Davidson and Leachman (2012), and to locate intermodal facilities or transport resources so as to exploit the advantages of the different transport networks available. These decisions can be distinguished in Alenezi and Darwish (2014) and Marufuzzaman et al. (2014).

In general, the involvement of several actors is unusual, except when network design is aimed at creating an impact that transcends the supply chain to the sector under study. For example, Davidson and Leachman (2012) contemplated multiple actors in distribution centres – importers – with the aim of evaluating risk grouping in delivery times, inventories and demand variability, with allocation and transport flow strategies being laid down for different groups of products. For their part, Fernandes et al. (2013) considered multiple actors at all stages of the chain with the aim of evaluating collaboration levels by shared use of infrastructure and determine the closure or opening of facilities that optimise profitability for all the actors involved.

Supply chain networks have been modelled with flows directed at supplying raw materials, distributing the finished product, and envisaging both supply flows and distribution flows throughout the network. In Marufuzzaman et al. (2014) supply flows are based on diminishing the effects of the likelihood of the interruptions that can occur in networks, with the installation of intermodal facilities that consolidate raw materials and enable flow continuity. This enables the design of a robust supply network that reduces unsatisfied demand. In distribution flows, Davidson and Leachman (2012) included the effects of unforeseen changes in demand, and Fernandes et al. (2013) introduced inventories in location-allocation decisions.

Table 2 Characteristics of location-allocation problems with intermodal facilities

References	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Transport chain networks								
Amaral et al. (2012)	ITO, OIF		DPF	AWN	R-R-R	A	S	Brazil
Guimarães et al. (2017)			DPF	AIF*	R-R-R	A	S	Brazil
Rothenbächera et al. (2016)			DAN	AWN*	R-R	C	M	Germany
Alumur et al. (2012)		U	O-D	EIF	R-A	PS	P	Turkey
Ishfaq and Sox (2012)			O-D	EIF	R-R-A	C	M	The USA
Kim et al. (2013)			O-D	AWN	R-R	C	U	South Korea
Santos et al. (2015)			O-D	AWN*	T-R	C	M	Belgium
Zhang et al. (2013)			O-D	AWN	R-R-R	C	M	Holland
Zhang et al. (2015)	ITO, OIF, GE	M	O-D	AWN	R-R-R	C	M	Holland
Supply chain networks								
Alenezi and Darwish (2014)	S, DC, ILF, RO		DAN	AIF*	R-R		M	
Hajibabai and Ouyang (2013)	S, ILF, RO		DAN	AWN	R-R	ME	BE	USA
Xie et al. (2014)	S, ILF, RO		DAN	EIF	R-R	ME	BE	USA
Marufuzzaman et al. (2014)	S, ILF, M		DPF	AWN	R-R-R	ME	B	USA
Davidson and Leachman (2012)	M, ILF, DC, RO	M**	DDF	AIF*	R-R-M	C	M	USA
Fernandes et al. (2013)	M, ILF, RO	M	DDF	AWN	R-R-M-P	ME	OD	Portugal
Kazemi and Szmerekovsky (2015)	M, ILF, RO		DDF	AWN	R-R-R-P	ME	GDF	USA

Notes: *Direct dispatch from the point of origin to the point of destination is also valid in transport chain networks, and from the installed logistics infrastructure to the point of destination in supply chain networks. **Multiple actors in ILF.

Contrary to what is observed in transport networks, the maritime mode is included in supply chain network models. However, it is included as a flow attribute and not a transport option for intermodal choices, as considered by Davidson and Leachman (2012) and Fernandes et al. (2013). Development of road and rail transport networks in the analysed geographic areas configure these as the two habitual intermodal modes.

The US mining and energy sector inspired several works related to IFLA in supply chain networks. The papers sought solutions to applications that range from the biomass supply to the distribution of biofuels, and oil derivatives such as ethanol, gasoline, diesel and aviation fuel.

6 Combined decisions in intermodal network design

Combined planning is defined in the context of network design as the design of a network of facilities and the arrangement of network services. When defining the network of facilities, it is necessary to be explicit about the type of facility for which a location is required, capacity limits, and the site's surface area. The services network design (Crainic, 2000) includes decisions such as selection and scheduling of the services to operate, the routing of freight, or the specifications of the terminal operations.

The *facilities* feature refers to the type of infrastructure required for the network to work. This infrastructure may be logistics centres and/or transport resources. *Capacity* limits are specified as a condition of the flow that can circulate around the network and determine *the surface area of the site* where the infrastructure is to be installed. *Logistics services* are the set of logistics activities that enable the continuity of the flow between modes. The *type of allocation* corresponds to the links permitted between infrastructure. These allocations can be single or multiple. *Costs* and *times* are the main attributes that affect allocation and are determined by the transportation modes analysed. The most significant findings in the literature are presented in Table 3.

6.1 Transport chain networks

Combined planning in transport chain networks intends the design of intermodal networks including hubs or intermodal terminals that provide services to the transport the freight. Services such consolidation/deconsolidation and classification are inherent to hub operations, whereas in intermodal terminals the only service required to provide is transhipment. In order to raise logistics and transportation competitiveness, networks of facilities are being designed under the concept of logistics integration centres. These centres not only provide the previously mentioned freight services, but have also been conceived generators of added value to the product, or to the operator (parking, restaurants, etc.). Guimarães et al. (2017) offered an example of proposals of this type.

Studies that define hub facilities are generally based on the hypothesis that there are no constraints on infrastructure capacity, as their purpose is to evaluate freight concentration at these points. In contrast, intermodal terminals and logistics integration centres do determine the facility's maximum capacity. For instance, Amaral et al. (2012) did so when evaluating any possible bottlenecks in the network and identifying better routes when diversions are required. Kim et al. (2013) defined capacities to assess network expansion options, and Zhang et al. (2013) also did so to analyse facility efficiency.

The site of the logistics facility is assumed to be a discrete area or it is done on a discrete-based network. Both alternatives assess potential sites for the infrastructure on the basis of a given complex network but in discrete-based network potential sites are subject to existing transport networks for each mode to be analysed.

The number of logistics infrastructure to be installed might be explicitly considered or by establishing the infrastructure capacity limits that intrinsically will define the required total capacity. The first of these options may be accompanied by a sensitivity analysis to address variations in the number of facilities, as in Alumur et al. (2012) and Amaral et al. (2012). Following the second alternative, Zhang et al. (2013, 2015) evaluated different network configurations by defining scenarios subject to different greenhouse gas emission price policies. Additionally, Guimarães et al. (2017) proposed the definition of the facility's minimum and maximum capacity.

Regarding the type of allocation, the consideration of economies of scale in the development of intermodal networks generally forces each node to be linked to a single intermodal facility (i.e., single-allocation), as in Alumur et al. (2012) and Zhang et al. (2015). Transhipment costs and transport costs are present in most of the models. Distances are taken into account for calculating the transport costs. Amaral et al. (2012) and Rothenbächera et al. (2016) applied the Euclidean distances rather than real (road) distances. The distance-cost ratio can be modelled as linear (see, e.g., Ishfaq and Sox, 2012) or by using economy of distance, as in Santos et al. (2015) where the fact that unit transport costs are inversely proportional to the distance travelled was applied. This last study conceives economy of distance as an opportunity to use more efficient transportation modes than road for long distances.

In addition, with respect to the research problem's intermodal performance, dispatch service times, transport operational times, service times at the facility, and waiting times at the facility are included in the models. Ishfaq and Sox (2012) model operations and waiting times at the facility, and Rothenbächera et al. (2016) evaluated the possibility of direct or intermodal dispatches with transport operational times. In contrasts, Kim et al. (2013) and Zhang et al. (2015) only considered transport operational times.

Other attributes, such as the speed permitted in the link, freight unit or vehicle capacity, and greenhouse gas emissions are both included in cost and time calculation and also considered to be constraints on the maximum flow that can be allocated to a link.

6.2 Supply chain networks

The design of the supply chain network is not only characterised by the inclusion of hubs and intermodal terminals, but also factories, distribution centres, and depots. For this type of network, however, hubs are located at intermediate points between suppliers and factories with the main aim of:

1. consolidating significant volumes of material
2. reducing the effects associated with possible interruptions to the primary transport, as in Marufuzzaman et al. (2014), or balancing the raw material's seasonal characteristic, as in Xie et al. (2014).

These two studies considered the installation of refineries and biorefineries where crude petroleum and biomass are transformed, respectively.

Intermodal terminals, distribution centres and/or storage depots are installed depending on the characteristics of the supply chain and the assessments of the distribution strategies that best adapt to them. Strategies related to import flows, direct and intermodal dispatches, and inventory result in intermodal terminals being defined with transhipment logistics, consolidation/deconsolidation, warehousing, and inventory management services and connectivity with different transport modes, as proposed in Davidson and Leachman (2012). To cope with seasonal demand, Xie et al. (2014) suggests to separate the processing stages for obtaining the final product with the installation of post-factory specialised intermodal terminals.

In an evaluation of intermodality as the only strategy for the distribution of multiple products, Kazemi and Szmerekovsky (2015) installed distribution centres, whereas Fernandes et al. (2013) installed depots. Freight transhipment is carried out at both of these infrastructure but the depots are conceived as areas devoted to long-term storage. Distribution centres and transitory intermodal points are installed to allow grouping of products from suppliers to retailers and inventory cost reduction. Alenezi and Darwish (2014) use transitory intermodal points in their model to perform freight transhipment.

When the focus is on supply chain networks, capacity is normally set as a global constraint. However, Davidson and Leachman (2012) and Alenezi and Darwish (2014) do not assume capacity limits since the considered flows are far from the actual capacity. Contrarily to the other works in supply chain, Fernandes et al. (2013) proposes a model having multiple decision makers and multiple flow allocations at all stages of the chain, so the use of the installed capacity need to be shared.

As in transport chain network design, the sites for the logistics facilities are chosen from a discrete space or a discrete set of candidates.

Transport distances and the transport mode are the base to compute transportation costs. Xie et al. (2014) proposed a direct relationship between distance and transportation costs, while Marufuzzaman et al. (2014) used the Hamming distance. Fernandes et al. (2013) set limits for each of the required services and transport mode rather than penalise distance.

Raw material processing times and replenishment times are included in the supply chain network design alongside transport operational times and service times. Fernandes et al. (2013) included raw material processing time to calculate the volume of the product flowing from the factory to the distribution centre during a defined period of time. Davidson and Leachman (2012) integrated materials replenishment times, as they modelled import flows and uncertain demands, which also required the modelling and management of inventories. Alenezi and Darwish (2014) and Xie et al. (2014) also considered inventories, but they do so at the distribution centre and the intermodal terminal, respectively. Meanwhile, Davidson and Leachman (2012) considered the inventory cycle, inventory in transit, and safety stock.

Finally, it must be highlighted that the studies that we found on the supply chain network design did not evaluate any aspects related to sustainability, and traffic travel speeds and freight units were used as performance metrics to assess the network's capability.

Table 3 Design of the intermodal network: location-allocation facilities

References	*Facilities network*			*Services network*								
	10	*11*	*12*	*13*	*14*	*15*						
						D	*X*	*I*	*T*	*S*	*V*	*C*
Transport chain networks												
Alumur et al. (2012)	H	N	D	F, C, D, T	U	+			+	+		+
Ishfaq and Sox (2012)	H	N	D	F, C, D, T	M	+			+			+
Rothenbächer et al. (2016)	H	N	D	F, C, D, T	M	+			+		+	+
Santos et al. (2015)	H	N	DN	F, C, D, T	M	+				+	+	+
Amaral et al. (2012)	IT	Y	DN	T	M	+					+	+
Zhang et al. (2013)	IT	Y	DN	T		+	+			+		+
Zhang et al. (2015)	IT	Y	D	T	U	+	+		+	+	+	+
Kim et al. (2013)	IT, TR	Y	D	T		+	+		+	+		+
Guimarães et al. (2017)	LIC	Y	DN	F, C, D, T, S	M	+						+
Supply chain networks												
Kazemi and Szmerekovsky (2015)	DC	Y	DN	T		+						+
Alenezi and Darwish (2014)	DC, TIP	N	D	C, D, T	U			+	+			+
Fernandes et al. (2013)	D, TR	Y	DN	T, A	M	+			+			+
Marufuzzaman et al. (2014)	H, M	Y	D	C, P	U	+				+	+	+
Xie et al. (2014)	H, M, IT	Y	DN	C, P, T, W	U	+		+	+	+	+	+
Davidson and Leachman (2012)	IT	N	D	C, D, T, W, I	U	+		+	+			+
Hajibabai and Ouyang (2013)	M, TR	Y	DN	P	U	+			+			+

7 Modelling location-allocation decisions

The third axis of discussion refers to the way in which decisions and parameters are considered for the mathematical formulation of location and allocation decisions on intermodal facilities and transport modes.

Network decisions responds to the infrastructure that will make up the facility network design. These may represent the closure or opening – use or setting up – of a facility that is selected from an existing set. This decision may entail the creation of new infrastructure or that certain actions be carried out that enable a facility to be used. *Allocation decisions* relates to the establishment of links between facilities and the product's flow through them. *Transport mode decisions* determines the transport mode on a specific link. Depending on the research problem's characteristics and the proposed intermodal network design, other specific aspects may be involved in the modelling. Some, such as *costs* and *times*, have been addressed in the preceding subsections. However, in the present section is explained the way in which they are represented from a mathematical standpoint. Table 4 positions the studied works with respect to the features considered in this axis.

7.1 Transport networks

Network decisions determine the opening (use) or not of the facility. However, defining it might entail the decision on the transport mode, as proposed by Alumur et al. (2012), and in other cases, be complemented to establish a pre-configuration of the facility network, as in Zhang et al. (2013, 2015). In addition, if the decision makers' objective is focused on reinforcing, redesigning or expanding the network, more than two options can be considered for the location decision. Kim et al. (2013) apply this strategy to define improvement actions to grow 'capacity levels' in relation to the attributes described in Table 3.

Allocation decisions relate to the way the services offered by the facilities can be accessed. It might be a single allocation, as in Alumur et al. (2012) or deciding on the transport mode, as in Ishfaq and Sox (2012), or determining the transport mode that will configure the intermodal combination. Allocation might consider the number of freight units or vehicles that travel along the links depending on the chosen transport modes. Rothenbächer et al. (2016) assessed the flow of direct dispatches and intermodal dispatches. Santos et al. (2015) complemented the decision with a limitation on the maximum number of transhipments. Zhang et al. (2015) use them to determine the transport mode that configures the intermodal network at the lowest cost.

Recall that the triangular inequality implies that making freight deviate from its origin-destination direct link to travel through an intermodal facility leads to an increase in the total distance (or time). In intermodal transport, those increments need to be compensated with discounts or returns to scale such the ones studied in Alumur et al. (2012). In relation to costs, transportation and transhipment costs are considered at the very least but, depending on the design of the intermodal network in question, set-up costs and the facility's fixed costs are also considered, as are the operational costs of consolidation between intermodal infrastructure, costs associated with greenhouse gas emissions, external costs, the cost of expanding the links and nodes, and costs associated with times and delays.

Transportation costs are generally considered by units of flow and mode. Santos et al. (2015) modelled these on the basis of transport vehicle gross weight and distance between terminals. Alumur et al. (2012) and Ishfaq and Sox (2012) included costs based on economies of scale to favour the installation of consolidation infrastructure. Transportation costs are also modelled as fractions depending on the cost generated in each section of the network, as it is done in Zhang et al. (2013, 2015).

Although the execution of several logistics activities is considered in the infrastructure, the modelled operational costs mainly correspond to transhipment costs by transport units and by transport modes. Exceptionally, Ishfaq and Sox (2012) represented the cost generated by the loading/unloading and consolidation/deconsolidation activities, thus reflecting the different flows inside the facility. Facility set-up costs and fixed costs are not usually considered. Some models envisage only fixed costs and integrate the two concepts into a single cost parameter. Examples of this are the Santos et al. (2015) and Guimarães et al. (2017) proposals for the first case, and Alumur et al. (2012) and Ishfaq and Sox (2012) for the second.

Concerns about the impact of the network on the environment are relatively recent and are generally focused on greenhouse gas emissions. Several models include these impacts as costs which, although they are not physical in nature, are used to minimise or restrict the network's contaminating effect. Considering environmental aspects affect both to location, allocation and mode selection decisions, and the execution of the logistics activities carried out in the selected infrastructure. In addition to the greenhouse gas emissions, local and global air pollution, congestion, traffic and noise pollution are integrated into intermodal network design. Santos et al. (2015) internalised all these factors, referring to them as external costs in the model.

Lastly, some complementary costs called transport times are considered for transport costs. These are generated on the basis of the time required for the transport operation to begin. This type of cost is defined by factors such as taxes, licenses, permits, interest, depreciation, and fall in the freight's market value during transport, among others. Zhang et al. (2013, 2015) model time costs, although the two proposals differ as to the shares allotted to transport and to produce. Transportation time costs depend on the transport modes that configure the network, whereas product times are separate.

In other respects, times are also regarded as a major aspect of modelling location-allocation problems. Operational times by transport modes contribute with optimal selection of the network's intermodal configuration and can even be considered for assessment of the efficiency of a specific mode, as is done in Rothenbächer et al. (2016) and Zhang et al. (2015) for round trip river transport and for rail mode. Ishfaq and Sox (2012) also considered waiting times for each type of service that freight requires at the facility and for this they model a G/G/1 queuing system in which arrival rate variability depends on transit time variability.

Intermodal transportation networks design problems are generally proposed as models that are deterministic in nature, i.e., every point's demand and the model's parameters are supposed to be known.

7.2 Supply chain networks

Supply chain models tend to consider a larger variety of decisions than transport network models. Fernandes et al. (2013) proposed decisions regarding:

1 opening, operating, and closing of the installed infrastructure

2 the amount of transport resources or equipment needed for each of the analysed transport modes

3 import and/or export volumes of all products and the volume of unsatisfied demand by customer, by product, and by organisation.

These variables are related to each supply chain's demand characteristics and behaviour. Xie et al. (2014) considered the unsatisfied demand linked to the seasonal behaviour of the modelled products, whereas Marufuzzaman et al. (2014) only considered the total quantity of unsatisfied demand.

In these networks, since facilities such as factories, distribution centres and depots are considered, decisions related to production and capacity need to be done. For example, Fernandes et al. (2013) and Xie et al. (2014) also decided the quantity of products to be processed in the factories for each of the analysed periods, and Kazemi and Szmerekovsky (2015) decided the capacity of the distribution centres that they install.

Depending on the model, the decision to install an intermodal facility or allocate a logistics infrastructure connected to a facility that is already installed lead to a modal configuration decision. This option refers to one of the distribution strategies designed for the supply chain, as proposed by Alenezi and Darwish (2014) and Davidson and Leachman (2012). Also, those papers modelling the flows throughout the network include decision variables to represent the flows that transit the chain using a specific transportation mode. Examples of this are Fernandes et al. (2013), Hajibabai and Ouyang (2013) and Kazemi and Szmerekovsky (2015). Except for Kazemi and Szmerekovsky (2015), these studies also included other decision variables representing the transport mode for flows between intermodal infrastructure. Exceptionally, Xie et al. (2014) declared auxiliary variables at the beginning of each period with which they determined the quantity of products to be stored at each facility in relation to product inventories and seasonality.

The main costs considered are set-up costs, facility fixed costs, and transportation costs. However, depending on the model, costs might include holding inventory, product import and export flow, transport resources, network disruption, raw materials purchase, production, warehousing and penalties for unsatisfied demand. If the network envisages the analysis of transport flows throughout the supply chain, transport costs are separated for each of the stages. When installing distribution centres between factories and points of consumption, Kazemi and Szmerekovsky (2015) divided transport cost between the two, and Alenezi and Darwish (2014) separated the transport costs for each stage according to the chosen distribution strategy. Fernandes et al. (2013) differentiated costs by period and transport mode. Finally, Hajibabai and Ouyang (2013) incorporated parameters that impact transportation times by increasing the capacity of the links that form the intermodal network.

Table 4 Modelling location-allocation decisions

References	*16*	*17*	*18*												*19*		
			A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*	*O*
Transport chain networks																	
Amaral et al. (2012)	A, H	C								+			+				
Rothenbächer et al. (2016)	A, H	C								+			+		+	+	
Santos et al. (2015)	A, H	C				+	+			+			+				
Alumur et al. (2012)	A, E, F	C			+		+		+	+			+	+	+	+	
Guimarães et al. (2017)	A, H	C					+			+			+				
Ishfaq and Sox (2012)	C, H	C			+		+			+			+		+	+	+
Kim et al. (2013)	A, G	C						+					+			+	
Zhang et al. (2013)	A, G, H	C		+						+		+	+				
Zhang et al. (2015)	A, G	C		+						+		+	+			+	
Supply chain networks																	
Xie et al. (2014)	B, H	C			+		+			+	+		+				
Fernandes et al. (2013)	A, C, G	C	+		+		+				+		+	+		+	
Marufuzzaman et al. (2014)	A, G, H	D			+					+			+				
Alenezi and Darwish (2014)	A, E, H	U			+						+		+		+		
Davidson and Leachman (2012)	A, G	U								+	+	+	+	+	+	+	
Hajibabai and Ouyang (2013)	A, E, H	C			+			+					+			+	
Kazemi and Szmerekovsky (2015)	A, H	C			+								+				

With regard to the network of facilities, it is normal to consider at the very least the cost of setting up the infrastructure. However, Davidson and Leachman (2012) omitted this cost, arguing that location decisions comply with an existing set of infrastructure. Apart from set-up costs, Fernandes et al. (2013) also included fixed costs and their respective amortisation periods.

Although a variety of logistics activities are considered for the infrastructure installed, operational costs mainly related to intermodal activities such as freight transhipment are not usually modelled. However, what is distinguished is the installation of transportation resources needed to facilitate the development of these activities. Hajibabai and Ouyang (2013) associated this decision as the cost of expanding infrastructure capacity, whereas Fernandes et al. (2013) associated it separately as the cost of transportation resources. As for other activities, Xie et al. (2014) included the costs related to the purchase of raw materials, which are considered separate from facility location in this case and dependent on transport in relation to the mode, quantity of products, journey distance and times. Inventory costs are also reflected in the modelling. Alenezi and Darwish (2014) proposed the cost of holding inventory associated with distribution centres, and Davidson and Leachman (2012) included safety stock costs and the costs of inventory in transit.

The surplus or lack of goods to comply with demand in a specific period becomes a cost (export or import cost) that is assumed without more detail. Fernandes et al. (2013) and Xie et al. (2014) considered costs for unsatisfied demand. Marufuzzaman et al. (2014) also included the cost that can be generated by interruptions to network links.

Transport times are usually considered in supply chain networks. Davidson and Leachman (2012) highlighted randomness of transport times in the case of the maritime mode. These times are also used to set the levels of safety stock in the supply chain, as stated by Alenezi and Darwish (2014). In addition, according to the Davidson and Leachman (2012) proposal, the inclusion of replenishment times between orders and freight consolidation/deconsolidation operational times enable the inventory cycles and inventory in transit to be modelled. Meanwhile, although Fernandes et al. (2013) did not consider the installation of factories, their model integrated the processing times of the different products distributed through the network.

Supply chain network design model proposals generally consider deterministic demands. In contrast, however, Davidson and Leachman (2012) and Alenezi and Darwish (2014) used risk grouping to model demand uncertainty. The former determined errors in demand forecasts based on normal distribution, while the latter assumed that they face a probabilistic demand modelled as a Poisson distribution at retail points. In both cases, uncertainty is compensated for by setting safety stocks.

8 Structure and resolution of the mathematical formulation

This fourth axis of discussion focuses on the structure of the mathematical formulation and analyses the resolution procedures proposed in the reviewed papers. It includes several features. Of these, the *objective function* represents the problem objective and is shown as a function of cost minimisation or profit maximisation, depending on the chain to be analysed. Moreover, it can comprise a single objective or multiple objectives. *Limitations* involves the problem's constraints. *Periods* refers to the consideration of the time in which the objective's optimisation is planned. *Mathematical programming model* *type* refers to the type of mathematical formulation and the way the problem has been modelled. *Resolution procedure* corresponds to the set of phases, techniques, and relaxation and breakdown methods used to achieve optimisation and provide the solution to the proposed research problem.

It is important to mention that we do not intend to offer a highly detailed description of the mathematical formulation in this section, but rather to highlight the most relevant elements in said formulation, as well as in the solving procedures used in the considered problems. Table 5 lists the features considered in the structure and resolution of the intermodal network design for each paper reviewed.

8.1 Transport networks

Decision-making in transport networks might consider several objectives. A way to reduce a multi-objective problem to a single-objective one is by aggregating several costs in one unique cost, as it is done in Amaral et al. (2012). Santos et al. (2015) also aim at minimise transport cost, but in line with the transport infrastructure's potential as a source of development, they considered government subsidies to incentivise intermodal activity and incorporated them as a way to reduce the cost. Some of the models are formulated using a bi-level approach, as in Zhang et al. (2013), with the upper level focusing on location decisions and the lower level for flow allocation decisions. But cost should not be the only objective (although it is usually employed to create a common weight) as, for example, in Kim et al. (2013) that chose lead and transport times as objectives to minimise.

The constraints affecting the model are related to the number of infrastructure to be installed, the allocation among the infrastructure, to ensure that flows move through the established intermodal links, to guarantee the continuity of the flow or to respect the facilities capacity. Limitations applied to transport times based on the required service times can be found in the Alumur et al. (2012) and Ishfaq and Sox (2012) models.

It is interesting to mention that other particular elements are specific to the context studied by each paper. Among them we find the maximum service times, the investment budget, and the allowed greenhouse gas emissions. Kim et al. (2013) included improvement actions connected with proposed network links expansion under the previously mentioned limitations. For their part, Zhang et al. (2013, 2015) considered greenhouse gas emissions to be subject to a fee for each kilometre travelled and tonne transported depending on the mode by which the freight flows.

Multi-period models have not been found in transport networks models. However, some approached the issue using different scenarios for each specific period of time. Amaral et al. (2012) used this strategy to analyse the changes produced in the network design when different datasets are included for each scenario.

Integer linear programming (ILP), mixed integer linear programming (MILP), mixed integer nonlinear programming (MINLP) and integer programming (IP) are the mathematical programming focuses used to formulate transport networks in combined decision-making for location, allocation and choice of transport mode.

Some of the proposed formulations are solved using exact methods. For example, Rothenbächer et al. (2016) used a branch and price and cut algorithm that considered the generation of columns and the lexicographic method to define lowest price allocations, the branch diagram to define the facilities to be used, and cuts accompanied by valid inequalities to relax link capacity restrictions. Despite developing a branch and bound algorithm, Ishfaq and Sox (2012) obtained results with excessive computational times for a small set of facilities. So, the need arises for alternative algorithms and they considered a taboo search to solve real size problems.

In some cases, the mathematical complexity of the models requires the use of specific tools to solve the problem, such as relaxation, or of simplifications. Alumur et al. (2012) limited the number of transport modes to two when configuring the network's intermodal focus and defined time commitments for deliveries. For this, they reformulated the base model and integrated new decision variables, as well as valid inequalities as restrictions. Rothenbächer et al. (2016) also used valid inequalities as a mechanism to strengthen linear relaxation. Ishfaq and Sox (2012) proposed a partial linear relaxation of a sub-problem of the original problem by changing the characteristics of the variables that determine both location and allocation. As a result, the reformulation is re-rendered as a lower bound for the original problem's optimal value.

Various approximate solution methods have also been proposed. For example, Kim et al. (2013) suggested that the problem should be decomposed into location (upper level) and allocation (lower level). Location decisions are solved with a genetic algorithm, whereas lower level decisions are solved with a shortest path algorithm. Compared to a listing algorithm, this approximating method offers quality results and reasonable calculation times. For their part Zhang et al. (2013, 2015) used a similar strategy in which the genetic algorithms were enhanced with more refined operators and strategies. Alumur et al. (2012) solved the coverage problem with simple heuristics and subsequently allocated transport flows by considering the corresponding costs. And Amaral et al. (2012) used a branch and cut algorithm with a processing time-based stop criterion formed around the definition of a gap.

A variety of commercial solvers (mathematical programming engines) are used to solve the proposed formulations and compare with the performance of the proposed solution procedures. These solvers include CPLEX, GUROBI, BONMIN, and GNU GLPK. Other tools such as TRANSCAD are used and enable the use of virtual networks based on geographic information systems.

8.2 Supply chain networks

Similarly to transport networks, decision-making in the supply chain might involve multiple objectives. Uniquely, Fernandes et al. (2013) proposed maximising profit for the various supply chain actors. To do this, their formulation included the contribution margin of each of the decision made in the multiple analysed periods.

In contrast to what is found in transport chain networks, costs generated by logistics infrastructure installation and transport resources are included in the supply chain function objective. Other differentiating features are related to inventory costs, the distribution strategy chosen for dispatches (direct or intermodal), order placement and percentage of orders satisfied at each retail point, as in Alenezi and Darwish (2014), and order replenishment and placement transport and operation times, as in Davidson and Leachman (2012). Meanwhile, Xie et al. (2014) minimised raw material purchase costs, production, and warehousing at each stage of the chain, and added a penalty cost for unsatisfied demand.

Another difference is the fact that costs related to the network usage traffic level are included in the transport costs. Thus, costs related to passenger flows are being considered in public networks, as proposed by Hajibabai and Ouyang (2013).

Moreover, the interruptions and emergency actions required to fulfil demand enable the consideration of transport costs incurred for direct dispatches. Marufuzzaman et al. (2014) included the negative consequences of disruptions in intermodal network links and the subsequent use of alternative routes in the transport cost.

It is not possible to define common limitations applied to the models in these formulations due to the specific characteristics included in each of the research problems. Some particular issues that restrict formulations can be the quantity of products to be manufactured related to the installed infrastructure and/or availability of raw material, the capacity of the facilities and the warehousing of the product during the different periods, and maintaining a flow in conjunction with falling product shelf life, as for example in Xie et al. (2014). Other particularities that constrain the problem are matching the transport used to the product type, the stage of the chain being modelled, and maximum permitted distances, as understood in Fernandes et al. (2013).

In contrast to what is observed in transport networks, supply chain's models do not include features related to their sustainability, but they do include an evaluation of different planning periods in some formulations. It is assumed for location decisions that once the infrastructure is installed, it remains open for all periods, but that the quantity of products to be manufactured, warehoused and distributed, and unsatisfied demand, are subject to the analysed periods. Xie et al. (2014) and Fernandes et al. (2013) proposed formulations that include other features. The latter also considered product volumes for import/export. In other cases, scenarios are created to evaluate the model's performance based on interruptions to the operability of the links as a result of natural phenomena, the evaluation of different intermodal configurations, and the availability of the existing facility network. These scenarios are studied in Marufuzzaman et al. (2014), Hajibabai and Ouyang (2013) and Kazemi and Szmerekovsky (2015) papers, respectively.

MILP and MINLP are the mathematical formulations used, to a greater extent, to define the proposed supply chain models. In these, location, allocation and transport mode decisions are not only represented by the type of variables and characteristics previously mentioned in transport chain networks, but are complemented with other decisions.

Procedures applied to solve the formulations include Lagrangian relaxation, benders decomposition, redundant restrictions or, possibly on some occasions, restricting the set of potential links through which the flows are dispatched. Applying Lagrangian relaxation enables low and high limits to be defined with polyhedral cuts, as is done in Alenezi and Darwish (2014), or a hybrid framework to be established that includes combined convex algorithms, as is done by Hajibabai and Ouyang (2013). When applying benders decomposition, Marufuzzaman et al. (2014) defined logical master cuts, optimal Pareto cuts, and valid inequalities to define the primal-dual for the sub-problem.

Heuristic techniques are also used to define the optimal distribution links in the network. Davidson and Leachman (2012) developed a heuristic to determine the location and applied a shortest path algorithm to determine allocation. Despite using the same allocation technique, Kazemi and Szmerekovsky (2015) used geographic location systems, such as ArcGIS, to make location decisions. As with the transport chain networks, problems were also solved using standard mathematical programming solvers.

Table 5 Structure and resolution of the mathematical formulation

References	*20*	*21*	*22*	*23*	*24*	*25*		
						A	*B*	*C*
Transport chain networks								
Amaral et al. (2012)	Min	UO	G	U	ILP		Branch and cut	CLPEX and GNU GLPK
Alumur et al. (2012)	Min	MO	E, F, G	U	MILP	Valid inequalities, promises of time	Heuristic	GUROBI
Guimarães et al. (2017)	Min	MO	G		MILP			CPLEX
Ishfaq and Sox (2012)	Min	MO	E, F, G	U	MILP	Lower bound, linear relaxation	Branch and bound, tabu search	BONMIN
Kim et al. (2013)	Min	MO	A, D, G		MINLP	Bi-level, big M	Genetic and shortest path algorithm	
Rothenbächera et al. (2016)	Min	MO	G		MIP	Valid inequalities, column generation	Branch and bound and price	CPLEX
Santos et al. (2015)	Min	MO	G		MIP			
Zhang et al. (2015)	Min	MO	D, G			Bi-level	Genetic and all-or-nothing algorithm	
Zhang et al. (2013)	Min	MM	D, G			Bi-level	Genetic and all-or-nothing algorithm	TRANSCAD
Supply chain networks								
Alenezi and Darwish (2014)	Min	MO	G	U	MINLP	Bi-level, redundant constraints	Lagrange	MATLAB
Davidson and Leachman (2012)	Min	MO	C, G	U	MINLP		Heuristic and shortest path algorithm	
Fernandes et al. (2013)	Max	MO	C, G	M	MILP		Heuristic	GAMS and CPLEX
Hajibabai and Ouyang (2013)	Min	MO	G	U	MINLP	Lagrange	Genetic and traffic assignment algorithm	
Kazemi and Szmerekovsky (2015)	Min	MO	B, G	U	MINLP	SIG	Shortest path algorithm	GAMS XpressMp
Marufuzzaman et al. (2014)	Min	MO		U	MILP		Benders decomposition	GAMS and CPLEX
Xie et al. (2014)	Min	MO		M	MIP			

9 Discussion and further research avenues

Current economic processes have turned intermodal transport into a strategic research field. The advantages of intermodal transport are maintaining the interest of researchers and academics in offering different solutions that assertively guide decision-making to tackle real problems caused by the requirements of integrated structures. This is the perspective that underlies this review and which differs from previous reviews (presented in Section 3) as it analyses the way that literature simultaneous addresses location-allocation planning problems in the design of intermodal networks. Joint decision-making for location, allocation, and choice of transport mode does not only involve transport networks perspective; supply chains also regard it as an effective management option for material flows.

In transport networks, features such as service times, greenhouse gas emissions, scale economies and products' potential for export are the most important factors. However, in supply chain networks, fluctuations in demand, turnover and inventory times, and interruptions to the network are the most relevant features. It also needs to be highlighted that the integrating nature of location-allocation problems entails the involvement of other decision makers; in transport networks, for example, governmental bodies are being included as the main actors, while in supply chains, transport actors are being considered passive subjects in decision-making.

Road and rail are the most frequent transport modes used in the intermodal configuration in both perspectives of network. However, the characteristics of the product being transported and the economic sector requiring the transport service determine the consideration of other modes that can be chosen. In this respect, it is important to highlight the fact that maritime transport is not considered as an option in the decision on the modal combination. This mode's long product transit times, the omission of long distribution networks from the analysis, the analysed sectors and products, and maritime transport's inherent complexity as a transport system, may explain why it is not considered in the model or why only the costs and times related to import and/or export flows are being assumed.

With regards to the integrated design of the intermodal network, location decisions do not always entail a decision to build new infrastructure, but also to optimise the network of existing facilities. This is more a characteristic of supply chain networks. The type of logistics infrastructure to be installed is tailored to the type of network being modelled. Factors such as bottlenecks, facility efficiency, network interruptions and expansion, raw material transformation, product seasonality, and distribution strategies stand out in the model as the facility's maximum installed capacity is accommodated. In transport networks, even though the proposed infrastructure combines a number of different logistics services, it is normal for these to be simplified in the modelling process with only transhipment being considered.

Allocation decisions are mainly determined by transportation costs and times, distances between infrastructure, traffic speeds in links, greenhouse gas emissions of the various transport modes considered, inventories and the capacity of the vehicles and the facilities. In contrast, a characteristic of supply chains is the definition of a single allocation in order to exploit the network's maximum installed capacity. The choice of transport modes that configure the network's intermodal focus determines location or allocation, and for this, the existing transport infrastructure in the analysed geographic area is considered. Notwithstanding, some proposals have extended the decisions to improving the chosen transport links – transport networks – or the installation of transport resources that make connectivity with the facility network possible and, as a result, the handling of intermodal activities – supply chains. It might be interesting to integrate the service times required for each dispatch or set of dispatches in the model as they also have an effect on allocation and transport mode decisions.

With respect to modelling, the simultaneous planning of location, allocation and transport mode decisions has mainly taken the form of MINLP and MILP, in which a set of binary variables enables the decision for both the location and the allocation of facilities, with the possibility of associating the transport mode to these. However, allocation decisions can also be represented by continuous variables depending on the vehicle or freight unit and product flow, respectively. From the perspective of the transport network, the approach has been completely restructured with the association of incremental improvement actions for the reconfiguration of the intermodal network, for which integer variables are required. From the perspective of the supply chain, other decision variables are frequently considered, such as the operation of the installed infrastructure, production levels, unsatisfied demand, import and export flows, and the transport resources to be installed.

Although the consideration of transport costs and transport operation times is repeated throughout the models, the set of proposed costs and times differ significantly depending on the type of network. In transport networks, there is a greater tendency to include the costs of operating the infrastructure that is installed, time, greenhouse gas emissions, and external costs. In contrast, these are not considered in supply chains, and the opposite viewpoint is taken, especially with regard to the last two, as current management trends are evaluated on the basis of adopting green logistics and sustainability concepts. However, as the network is managed at the chain level, costs relating to the purchase of raw materials, production, warehousing, inventories in transit, unsatisfied demand and any possible interruptions that may occur, are all included.

With regard to set-up costs, it is important to stress that they are included in supply chains, whereas they are not normally considered in transport networks. There may be two reasons why this distinction occurs: first, because the real problem requires redesigning or reconfiguring the facility network and, second, due to the involvement of investors among the network actors. Emphasising the latter, it is common for infrastructure to be financed by the network's own actors in supply chains, whereas, on the contrary, investors can be governmental bodies or public-private partnerships in transport networks, depending on the sector and the geographic area analysed. They are not normally included among the decision makers in these models.

As far as resolution techniques are concerned, the complexity of the problems entails the use of decomposition or relaxation methods. The convergence of two planning horizons (strategic and tactical), the selection of the transportation mode, two perspectives of network design and, as a result, the characteristics implicit in each of these, enrich the set of heuristic and metaheuristic techniques that can be used. It is important to highlight that it's the main objective that prompts the design of these networks, more so even than minimising costs and maximising profits, possesses an inherent functional character that contributes, among other things, through compliance with aspects of public policy, flexibility, sustainability, and competitiveness.

The reviewed research efforts have proven the efficacy of mathematical programming for the simultaneous planning of strategic-tactical problems in intermodal network design. However, additional research is required to shed light on emerging features of transportation's economics or to ensure that the results of research are better suited to the needs and difficulties faced in practice. For example, future studies should stress the development of models directed at optimising economic processes, integrating the supply chain and transport chain actors, considering sustainability, accessibility and connectivity issues in a wide range of geographic environments, and the use of solution techniques that enable uncertainty, the volatility of investment budgets and the evolution of the network design over time to be evaluated.

The convergence of location and allocation decisions and the choice of mode among transport chain and supply chain actors benefits the integration of key processes, the specialisation of the logistics sector, drives up company profits and improves the competitiveness of an economic sector, region or country. Collaboration and cooperation between actors and synchronising intermodal activities in the network are essential for achieving an affinity of decisions. Assessing these initiatives on the basis of the concepts of synchro-modality and the physical internet is equally appealing for designing and redesigning flexible and dynamic intermodal networks whose maximum installed capacity can be exploited.

It would also be interesting to highlight the active involvement of governmental bodies and the evaluation of investment requirements for infrastructure in forthcoming studies. If financial and budgetary support is considered, be it partially or fully, this optimises the decision on the basis of the efficient allocation of currently available and planned economic resources. Apart from generating profitability, governmental bodies are inclined toward local and economic development, and this would reflect an intermodal network designed in accordance with the principal productive, economic, social and geographic needs of the analysed area or region. These initiatives can be modelled with multi-criteria, multi-objective focus accompanied by indicators that enable the measurement of the effects of the decisions being evaluated.

It is also important that the studies that will be produced analyse the viability of designing intermodal networks in areas with low accessibility and territorial connectivity indexes, a lack of well-connected transport systems, or with geomorphological features that facilitate and adapt to intermodal transport. The importance of this lies mainly in the requirements of developing countries to face up to the challenges of creating competitive regions by identifying logistics infrastructure and transport projects to support increased industrial density, improved quality of life and, in the final analysis, contribute to territorial development and the strengthening of domestic and world trade. It is important that location decisions should not be skewed toward defining logistics infrastructure in these initiatives, but also involve the construction or adaptation of infrastructure and transport resources.

In other respects, concerns for developing and promoting sustainable regions should go beyond the evaluation of fees and costs related to greenhouse gas emissions produced by logistics activities and mode substitutions. Generating initiatives that evaluate the impact of intermodal networks designed to be consistent with natural reserves, ecological interests, and settlements of protected populations, while also responding to the environmental and social needs of the area under study, enable interventions to be made in the territory that reduce the negative impact that the implementation of the designed network might have. These initiatives also promote interest in research into green logistics, thus requiring the integration of IT and communication technologies that enable material and information flows of all the network's addresses to be controlled and monitored.

Lastly, other interesting initiatives include the development of heuristics and metaheuristics that enable the tackling of large-size problems, the formulation of multiple objective, multiple criteria and multiple period problems, the uncertainty inherent in network design and the availability of the investment budget. Simultaneous IFLA planning problems require solution techniques that rapidly respond to the custom optimisation that escalates model data and, therefore, the number of variables that the model must assess. Considering multiple objectives with multiple criteria, multiple actors, multiple products and multiple periods adds degrees of complexity, as each has to be efficiently responded to. Likewise, considering the uncertainty of the data associated with different occurrence scenarios enables the evaluation of the feasibility and optimality of alternative solutions for the network being designed. The guidelines framed for these features would establish a differential in the literature and contribute methodological advances in techniques such as multi-staged stochastic programming.

10 Conclusions

This study provides a SLR of the research related to the design of intermodal freight transportation networks. The review adopts a two-stage methodology merging a comprehensive first stage that analyses recent surveys to establish the guidelines and criteria that enable the subsequent systematic review in the second stage. The review concentrates on analysing contributions to the current state of the art on intermodal freight transportation. Axes of discussion as:

1 the characteristics of the research problem

2 the particularities of intermodal networks' design decisions

3 the aspects considered when modelling facility location-allocation problems

4 the formulation and proposed solution approaches, are used to classify and analyse the different contributions.

Our analysis confirms that the two dominant research perspectives in the related literature, namely transportation networks and supply chain, focus on different aspects and adopt different approaches to address them. These differences extend to the nature of the proposed models and formulations. From the perspective of the transport networks, models are aimed at capturing incremental improvement actions for the reconfiguration of the intermodal network while, from the perspective of the supply chain, other decisions are frequently considered, such as the operation of the installed infrastructure, production levels, unsatisfied demand, import and export flows, and the transport resources to be installed.

However, and in spite of these considerable efforts, additional research is required to shed light on evolving aspects of transportation's economics or to ensure that the research's results are better suited to the needs and difficulties faced in practice. This review identifies and discusses some of which we consider to be the most relevant or urgent ones, and includes emerging concepts of synchro-modality and the physical internet is equally appealing for designing and redesigning flexible and dynamic intermodal networks whose maximum installed capacity can be exploited.

Finally, we believe that, despite the enormous efforts devoted to support the complex decision-making processes related to intermodal freight transportation networks design, a lot remains to be done within this field. We strongly believe that it continues to present very interesting, challenging and relevant opportunities from both research and practical perspectives.

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