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

Abstract

This systematic literature review focuses on planning models addressing the simultaneous location-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. Key aspects identified in the first step such as (1) characteristics of the research problem, (2) particularities of intermodal networks' design, and (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 discussed.

Keywords: Systematic Literature review; Intermodal network design; Location-allocation problem; Intermodal freight transport; Mathematical programming; Modelling; Optimization Techniques; Intermodal Facilities.

1. Introduction

Intermodal freight transport is basically defined as the movement of a single freight unit using two or more transportation modes (European Conference of Ministers of Transport, 1993) Appropriate facilities are required for the freight to be transshipped from one transportation mode to the other (Sörensen et al., 2012) as well as transport resources, consolidation and deconsolidation logistics activities, classification, warehousing and distribution that enable products to flow along the facility network (Bhattacharya et al., 2014).

These requirements impact both the design of the facility network and the design of network services. However, these design activities are considered at different decision levels (Crainic and Kim, 2007). The design of the facility network is on a strategic management level and includes decisions about the facilities' locations, types and capacities ((Macharis and Bontekoning, 2004). Network services design is on a tactical decision level and is concerned by the optimal use of the facilities based on services and transport modes (SteadieSeifi et al., 2014).

The research concerned by the simultaneous planning of both facility network design and network services design falls within the location-allocation literature. Simultaneous objectives of location-allocation are: (1) determining the best locations for facilities that offer the best service to a set of points of demand, and (2) ascertaining each point of demand's allocation to the facility that best serves it (Ostresh, 1975; Cooper, 1963; Scott, 1970). In other words, the aim is to optimize both facility location and links between facilities to satisfy demand while minimizing total costs (Azarmand and Jami, 2009). Simultaneous location and allocation planning including intermodal transport can generate a competitive advantage for the supply chain through the efficient use of transportation networks (Ishfaq and Sox, 2012; Alenezi and Darwish, 2014) and by enabling the integration of decision-makers (Govindan et al., 2017).

Although it is possible to solve location-allocation problems with techniques such as simulation (Crainic et al., 2017) and virtual reality (Phoon et al., 2017), mathematical programming techniques are mainly used due the accuracy required in the solutions and the complexity of the problems in time and solution costs (Dybskaya and Sverchkov, 2017; Arabani and Farahani, 2012; Djafar et al., 2015). Mathematical programming has played a fundamental role in solving location-allocation problems in the field of IT and telecommunications networks (Klose and Drexl, 2005; Ogryczak et al., 2014), and in managing human aid distribution and disaster response (Safeer et al., 2014). Caris et al. (2014) propose that adding decisions about intermodal transport to location-allocation decisions creates significant problems for programming techniques and the solution methods required to optimize the problem.

We, therefore, consider a systematic literature review (SLR) to be timely and appropriate for establishing how mathematical programming has been used to address simultaneous strategic-tactical location-allocation problems in the specific context of intermodal transport in relation to the following four key points: (1) characteristics of research problems, (2) design of intermodal networks, (3) components, variables, and parameters that determine the integration of decisions about location, allocation, and choice of transportation mode, and (4) proposed solution approaches.

The present SLR differs from earlier literature reviews in that it proposes a novel analytical structure for the planning of strategic-tactical problems in the context of intermodal transportation that enables their deep understanding, the creation of differentiating knowledge, and the identification of future research lines. Furthermore, the present SLR is relevant as it recognizes the great importance of freight movement in two close yet different trending research streams (transport networks design and supply chain management) and so offers parallel analyses for each of the key points mentioned in the preceding paragraph.

This paper is organized as follows: Section 2 review the taxonomies published in the literature that are closely related to intermodal freight transport and mathematical programming techniques in order to identify whether intermodal facility location-allocation has previously been analysed and to define guidelines to study of the chosen references. Section 3 describes the methodology used in line with each of the steps in SLR methodology. Section 4 presents the main findings for the 16 chosen references in accordance with the core aspects defined. Section 5 discusses proposals for future studies. Lastly, Section 6 presents the final considerations.

2. Intermodal transport and mathematical programming in the literature: previous reviews

Research interest has been growing in the area of intermodal freight transport since the 1990’s (Agamez-Arias and Moyano-Fuentes, 2017). According to Mathisen and Sandberg (2014), publications on intermodality can be found in over 100 scientific journals spanning a range of research areas. A linked two-stage process was conceived for this review. The first stage is detailed below and consists of the analysis of 10 taxonomies closely linked to intermodal freight transport and mathematical programming techniques in order to identify the way that intermodal facility location-allocation problems have been addressed. These findings enable guidelines to be drawn up for the application of SLR methodology in the second stage, in Section 3.

The 10 taxonomies have been chosen for their significance in the citations index and by cataloguing a broad spectrum of problem areas associated with intermodal freight transport. The analysis has been conducted according to CIMO logic—Context, Intervention, Mechanisms and Outcomes—as proposed by Tranfield et al. (2003). The 10 taxonomies were sorted into two groups. The taxonomies related to analysing intermodality in the area of the transportation chain were put in the first group, while those that plan supply chain management were placed in the second group.

Bontekoning et al. (2004) was identified as one of the first papers in the transport chain group to present a state-of-the-art study of intermodal transport. These authors propose a future research agenda mainly directed at designing the terminal network, profit sharing among multiple actors, and developing operations research techniques. In response to the last of these, Macharis and Bontekoning (2004) present a literature classification that analysed research problems that had been examined for each of the decision-makers (network, terminal, intermodal and drayage) on each of the planning levels (strategic, tactical and operational).

Caris et al. (2008) present an update on the above proposal but with an inverted classification focus, i.e., they analyse the problems that correspond to each of the decision-makers on each of the planning levels. They also devote a specific section to the analysis of 6 problems that impact multiple planning levels or multiple decision-makers. An examination of these references leads to the conclusion that even though they are not location-allocation in type, it is important to regard them as an approach to simultaneous planning issues. SteadieSeifi et al. (2014) propose an update to the literature using the same focus approach.

Caris et al. (2013) present a classification that distinguishes between terminal network design problems and network service design problems. An examination of the references showed that the Ishfaq and Sox (2012) and Zhang et al. (2013) proposals cited in the first of these categories are worthy of being analysed as they address simultaneous intermodal facility location-allocation planning problems. Agamez-Arias and Moyano-Fuentes (2017) propose a review of conceptualization, the economic efficiency of intermodal systems and optimization models. Lastly, Caris et al. (2014) suggest integrating intermodal transport decisions and supply chain decisions.

At the same time, paradigm shifts in supply chain management have transformed planning processes toward a system focus that requires identification and integration of processes and network actors (Mentzer et al., 2001; Lambert et al., 1998). Customer satisfaction and materials flows not only impact procurement, production and inventory decisions, but also decisions on transportation, distribution channels and arrangements with carriers and other actors of interest for the supply chain (Felea and Albastroiu, 2013) in which agility and response capability are important for the supply chain network (Yamada and Febri, 2015).

According to Dekker et al. (2012), product characteristics, travel distances, terminal location, actor coordination, and freight transport unit affect transport capacity, speed, economy and environmental performance in the supply chain. Lam and Gu (2013) highlight the need to design and develop sustainable intermodal networks to optimize the flow of containers and to include the port hinterland in the network. Rožić et al. (2016) stress that consideration should be given to the incorporation of inland intermodal terminals.

Lastly, it is important to mention that other taxonomies were considered that analyse some aspect or isolated decision but which do not fully address our review's objective. These include Alumur and Kara (2008), Campbell and O'Kelly (2012) and Farahani et al. (2013), who review location decisions for hubs, Crainic (2000), who proposes designs for network services, and Crainic et al. (2017), with regard to simulation applied to intermodal freight transportation problems. Also Contreras and Fernández (2012), who focus on the transport chain, and Bravo and Vidal (2013), who in their supply chain focus analyse simultaneous decision planning but do not reference models that involve transport mode selection models.

Figure 1 shows the main characteristics of these 10 taxonomies and Figure 2 the future research lines proposed in each study.

Fig. 1 main characteristics of each of the 10 analysed taxonomies

Fig. 2 future research lines proposed in each study

Our analysis of the taxonomies enabled us to specify the following guidelines for systematic literature review:

a) As far as we know, mathematical programming techniques have not been used in the literature to analyse simultaneous intermodal facility location-allocation planning problems, so they have great review potential.
b) 2012 was determined as the first year of the period defined for the reference search as it is the year in which Caris et al. (2013) identify the first two papers related to simultaneous location-allocation planning of intermodal facilities. It is important to mention that problems of this type may exist in the literature prior to this, however, the frequent proposal of classification according to the classic planning levels and reiterated suggestions as a future research line when linking decisions with different planning horizons allow us to consider that problems of this type have been examined in the recent literature.
c) Intermodal facility location-allocation problems can not only be addressed from the perspective of transport network design, but also from that of supply chain network design. As such, some of the search criteria have been expanded with the specific addition of some new keywords: “integrated planning” and “supply chain”. This has enabled the sphere of research to be broadened to include business and planning topics.
d) It is important to define aspects that lead to an appropriate analysis of problems of this type due to their integrative nature and to the referenced taxonomies limiting their appropriate assessment. Moreover, the future lines of research in the references advise to concentrate on aspects related to sustainability, geographic area of study, territorial connectivity and accessibility, and capturing uncertainty through stochastic programming models.

3. Methodology: Systematic Literature Review

The sequence of steps proposed by Denyer and Tranfield (2009) for the systematic literature review to be applied enables a thorough examination of the literature, the selection of references that really represent the objective of the review, the findings to be mapped out through novel proposals, and gaps to be identified in the literature that can represent future research lines. These characteristics adapt perfectly to the object of our review, which is oriented toward determining the state of research into facility location-allocation problems in the design of intermodal freight networks that apply mathematical programming as the modelling technique. Taxonomic analysis in Section 2 enabled the objective to be clarified as well as the inclusion of new search criteria and the definition of aspects that allow the selected papers to be evaluated.

The following decisions had to be made to locate these papers: search engines, key words, and search strategies. The WOS and Scopus scientific databases were chosen as the search engines as they contain a significant number of papers published worldwide related to the topic under review. The key words initially defined were: intermodal transport, intermodal freight transport, location-allocation problem, network design, intermodal network design and mathematical programming. However, as stated in the analysis described in the previous section, new keys words were added: integrated planning and supply chain. The area of research was not limited and the last two led to results being retrieved related to the areas of economy and business, and planning and development, which broadened the initial perspective skewed toward the areas of transport and operations research. Search strategies used were: a) apart from the basic search, the snowballing technique was also used in the search for the cited reference to broaden the collection of papers, b) Boolean operators were used to combine key words and create search strings, and c) when the search was run with the terms “transport” and “intermodal”, the decision was taken to truncate the term transport to include the various derivations of the word and to replace the term “intermodal” with “multimodal, "synchromodal" and "co-modal"[1] to represent the different meanings of intermodality found in the literature.

Selection and evaluation of the papers was performed with great care as simultaneous planning problems are not only related to location-allocation but also location-routing and location-inventory (Alizadeh, 2009). Several filters were therefore applied. The first checked the title and ensured that it and the abstract were connected with the formulated question. 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 solve the problem. The type of papers selected were peer-reviewed articles published from 2012 to 2017. Excluded documents included conference proceedings, reports, books, book chapters, and theses/dissertations. These criteria enabled 16 references to be selected for subsequent analysis and synthesis.

With the aim of carrying out a differencing review proposal we deemed it suitable to analyse each of the papers by breaking it down into four main points, each of which contains a group of key aspects that facilitate evaluation and understanding. The guide for defining these aspects and the guidelines mentioned in Section 2 was the assessment framework presented by Azarmand and Jami (2009), Alizadeh (2009), and Bravo and Vidal (2013) for simultaneous planning problems, as they allow a full analysis of each of the selected papers. The make-up of the four groups was based around: (1) the characteristics of the research problem, (2) how intermodal networks are designed, (3) the components, variables, and parameters that are determinants of integrating location, allocation, and transport mode selection decisions, and (4) 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 conceptual framework for the literature analysis and, in particular, the defined aspects and the way that these are grouped together under the proposed key points. Section 4 presents the results obtained for each of these.

Table 1 Key aspects in the simultaneous planning of location-allocation of intermodal facilities

	Aspects	Description	
Characteristics of the research problem			
1	Network	Transport chain network (TCN), Supply chain network (SCN)	
2	Actors	TCN: Intermodal transport operator (ITO) Operator of intermodal facilities (OIF) Government entities (GE)	SCN: Suppliers (S) Manufacturers (M) 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 (DP) Directed distribution flows (DD)	Directed flows along the network (DAN) Flows of origin-destination pairs (FO-D)
5	Intermodal Focus	Before the intermodal facility (BIF) After the intermodal facility (AIF)	Between intermodal facility (EIF) Along whole network (AWN)
6	Transport modes	Road-Air (R-A) Road-Rail (R-R) Road-Rail-Air (R-R-A) Road-Rail-Maritime (R-R-M)	Road-Rail-River (R-R-R) Road-Rail-Maritime-Pipelines (R-R-M-P) Road-Rail-River-Pipelines (R-R-R-P)

[1] According to SteadieSeif et al. (2014) and Agamez-Arias and Moyano-Fuentes (2017), these terminologies have been used recently to refer to the use of two or more modes of transport.

7	Sector	Agricultural (A) Container (C)	Mining and energy (ME) Parcels services (PS)
8	Product	Biomass (B) Biomass and ethanol (BE) Gasoline, diesel and aviation fuel (GDF) Oil derivatives (OD)	Parcels (P) Soya (S) Single (U) Multiple (M)
9	Geographic Area	Belgium, Brazil, Germany, Holland, Portugal, South Korea , The US, Turkey	
Simultaneous decisions in intermodal network design			
10	Facilities	Depots (D) Distribution centre (DC) Hub (H) Intermodal terminal (IT)	Logistic integration centre (LIC) Manufacture (M) Transitory intermodal points (TIP) Transport resources (TR)
11	Capacity	Yes (Y), No (N)	
12	Installation space	Discrete (D), Discrete base network (DN)	
13	Logistics services	Classification (F) Consolidation (C) Deconsolidation (D) Inventory management (IM)	Production (P) Support services (S) Transshipment (T) Warehousing (W)
14	Type of allocation	Single (U), Multiple (M)	
15	Allocation attributes	Distances (D) Greenhouse gas emissions (X) Inventories (I) Times (T)	Speeds (S) Vehicle capacity or freight unit (V) Transshipment costs and transport costs (C)
Modelling facility location-allocation problems			
16	Focus model	Integer linear programming (ILP) Mixed integer linear programming (MILP)	Mixed integer nonlinear programming (MINLP) Mixed integer programming (MIP)
17	Decision / Variable	Facility location / Binary (A) Facility location with capacity / Binary (B) Facility location in operation / Binary (C) Facility location and transport mode / Binary (D)	Allocation / Binary (E) Allocation between facilities / Binary (F) Allocation and transport mode / Integer (G) Amount of product per link / Integer (H)
18	Demand	Certainty (C), Uncertainty (U)	
19	Costs	Closing costs of the facility (A) Costs of greenhouse gas emissions (B) Establishment costs of the facility (C) External costs (D) Fixed costs in the facility (E) Link expansion costs (F)	Operational costs between facilities (G) Operational costs in the facility (H) Storage costs (I) Times costs (J) Transportation costs (K)
20	Times	Operational time in the facility (L) Shipping service time (M)	Transport operational time (N) Wait time (O)
Formulation and resolution			
21	Optimization type	Minimize (Min), Maximize (Max)	
22	Function objective	Mono-objective (UO), Multi-objective (MO), Multi-objective multi-criteria (MM)	
23	Limitations	Greenhouse gases emission (A) Facility capacity (B) Inventories (C) Investment budget (D)	Shipping service time (E) Transport operational time (F) Common limitations (G)
24	Periods	Single (U), Multiple (M)	
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.	

4. Intermodal network design: Location-allocation of intermodal facilities

This section presents the obtained results for each of the four keys analytical areas shown in Table 1. The specific aspects to be analysed in each area are defined and subsequently, the findings are described. Also, the selected articles are grouped naturally according to whether they adopt the transport chain perspective or the supply chain perspective as this enables a better understanding and analysis of the characteristics that represent them.

4.1. Characteristics of the research problem

To establish the characteristics of the research problems of intermodal facility location-allocation planning, it is necessary to detail the aspects that describe the intermodal network to be designed. The type of *Network* provides a contextualization and extension outline that enables the size of the research and the actors involved to be defined. *Actors* are the decision-makers and can differ depending on the type of network. Different types of actors require different components that affect decisions to be included in the model, as will be presented in Section 4.2 for example, in a transport chain, decisions are more connected with fulfilling a transportation service (schedules, delays, etc.), while supply chain networks focus on exploiting infrastructure capability (inventories, etc.)

Actors by type provides a vision of integration, collaboration, and alignment of company objectives throughout the network. Although a greater number of decision-makers increases the model's complexity, decision options are more in line with reality as they consider the requirements of all of the decision-makers in the model. The *Type of flow* represents the direction of freight traffic in the network links. The *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 problems described in each of the articles considered in this literature review.

<u>Transport Chain Networks</u>

Generally-speaking neither the actors that make up the network nor the number of actors involved are explicitly mentioned in networks designed under the concept of the transport chain. However, it is possible to deduce the involvement of intermodal transport operators and of intermodal terminal operators from the approach to location and allocation decisions. Drayage operators can also be distinguished in cases involving direct dispatches with partial or smaller size freight, divisible/indivisible dispatches or network entries/exits. Apart from the first two mentioned operators, Zhang et al. (2015) exceptionally refer to governmental bodies being included as decision making actors and the consideration of multiple actors by type. The present study assumes an objective for each of the decision-makers in the model, with all the actors subject to the objective set by governmental bodies.

Transport flows have mostly been modelled with flows of origin-destination pairs in which each node in the network is considered both a point of origin and a destination. Despite networks usually being planned with flows of this type, models have been proposed that bear little relation to this perspective. The distinction is presented by the need to improve the export potential of the product under study and this involves considering dispatches as directed procurement flows, as stated by Amaral et al. (2012) and Guimarães et al. (2017). Meeting delivery times for different service requirements enables directed flows to be defined along the whole network, as proposed by Rothenbächera et al. (2016).

Three ways have been found of representing the intermodal focus. In the first, intermodality is performed on the basis of the installed intermodal infrastructure. This type is distinguished with the aim of encouraging intermodal activity and directed flows are defined for this. An example of this can be found in Guimarães et al. (2017). In the second way, intermodality is developed between intermodal infrastructures installed with the goal of boosting the effects of scale economies by attracting and consolidating freight. This effect is particularly important in the studies by Alumur et al. (2012) and Ishfaq and Sox (2012).

In the third way, the intermodal focus is present throughout all the network links with the co-existence, in certain cases, of different transportation mode options for the same link. The speed with which the transport vehicle moves, the link's 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), Rothenbächera et al. (2016), and Guimarães et al. (2017) envisage direct freight dispatches from the point of offer to the point of demand in parallel with the proposed intermodal focus. Direct dispatches are for partial freight loads, divisible/indivisible freight loads or meeting service times for which road transport is allocated.

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 area or zone being designed. 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 the configuration 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 lie, on the one hand, in the complexity of integrating decisions that underlie 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 containerized—comprising a single or multiple products—, based on the strong influence of local development and international trade in Brazil, Amaral et al. (2012) and Guimarães et al. (2017) focus on modelling a network subject to agricultural sector flows, especially soya. Meanwhile, in the expectation of responding to simultaneous location and allocation decision making for a single actor, Alumur et al. (2012) analyse 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. Simultaneous location-allocation planning of intermodal facilities in transport chain networks in countries such as Germany, Belgium, South Korea, the US, Holland and Turkey is aimed at improving the efficiency of the service provided by optimizing existing infrastructure and 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 to integrating and expanding transportation networks in the different available modes.

Supply Chain Networks

The actors involved in networks designed under the concept of the supply chain depend on the stages of the chain included in the model and include suppliers, manufacturers, distribution centres and retail outlets. Some of the transport chain actors can be identified as being considered passive subjects in planning in some of the approaches. This, by reason of the allocation of the flow to existing logistic intermodal infrastructures, as can be understood in Davidson and Leachman (2012), and the need to locate intermodal facilities or transport resources so as to exploit the advantages of the different transport networks available in the area of the supply chain, decisions which can be distinguished in Alenezi and Darwish (2014) and Marufuzzaman et al. (2014).

In general, the involvement of several actors by type is not usual 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) contemplate 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) consider 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 optimize 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 a robust supply network to be designed that reduces unsatisfied demand. In distribution flows, Davidson and Leachman (2012) include the effects of unforeseen changes in demand, and Fernandes et al. (2013) resupply times and rotation of different products, thus highlighting the integration of inventory in location-allocation decisions. Flows throughout the network lead to chain configurations based on infrastructure location that determine the chain’s central structure. Models of this type can be found in Alenezi and Darwish (2014), Hajibabai and Ouyang (2013), and Xie et al. (2014).

The intermodal focus is closely linked to the motivations that exist in transport chain networks, especially in those where the transport flow extends throughout the network, as existing transport networks are used when intermodality is included in location and allocation decisions. As a result, there is a tendency to consider transport infrastructure and resources in location decisions or to make use of existing intermodal infrastructure to develop flow allocation strategies according to demand requirements. This aspect is examined in detail in Section 4.2.

Contrary to what is observed in transport chains, the maritime mode is included in supply chain network models. However, it is included as a flow attribute and not a transport option for intermodality, as considered by Davidson and Leachman (2012) and Fernandes et al. (2013). Hazard and risk characteristics associated with the safe transportation of products merits evaluation of the pipeline mode. 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 champions proposals for simultaneous location-allocation planning in intermodal supply chain networks. The models seek solutions that range from the optimization of biomass supply to the distribution of biofuel, and oil derivatives such as ethanol, gasoline, diesel and aviation fuel. Fernandes et al. (2013) also assess this sector in the Portuguese supply chain.

Table 2 Characteristics of location-allocation problems with intermodal facilities

References	Characteristics							
	2	3	4	5	6	7	8	9
Transport Chain Networks								
Amaral et al. (2012)	ITO, OIF		DP	AWN	R-R-R	A	S	Brazil
Guimarães et al. (2017)			DP	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 US
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	The US
Xie et al. (2014)	S, ILF, RO		DAN	EIF	R-R	ME	BE	The US
Marufuzzaman et al. (2014)	S, ILF, M		DP	AWN	R-R-R	ME	B	The US
Davidson and Leachman (2012)	M, ILF, DC, RO	M**	DD	AIF*	R-R-M	C	M	The US
Fernandes et al. (2013)	M, ILF, RO	M	DD	AWN	R-R-M-P	ME	OD	Portugal
Kazemi and Szmerekovsky (2015)	M, ILF, RO		DD	AWN	R-R-R-P	ME	GDF	The US

* 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

4.2. Simultaneous decisions in intermodal network design

As upheld in the introduction to this paper, simultaneous planning in network design implies the design of a network of facilities and network services. The first of these is a strategic perspective and takes into consideration the location of the facility. For this, it is necessary to be explicit about the type of facility for which a location is required, capacity limits, and site surface area. The second is characterized by a tactical perspective in which aspects that define allocation are listed. Among these, we can cite the logistics services to be offered at the facility, the type of allocation and distances, and times and costs depending on the transportation mode. Costs corresponding to every aspect are conceived—or not—in each of the perspectives. These will be analysed in Subsection 4.3.

Facilities means the type of infrastructure required for the network to work. This infrastructure may be logistics centres and/or transport resources. With the type of infrastructure, *capacity* limits are specified as a condition on 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 and the development of intermodality. The *type of allocation* corresponds to the links permitted between infrastructures. 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 in the model. Additional attributes may be considered depending on the proposed models.

Being consistent with the integrative nature of location-allocation problems of intermodal facilities, the most significant findings in the literature are presented in the following, maintaining the difference between transport chain networks and supply chain networks. Table 3 lists the main aspects.

<u>Transport Chain Networks</u>

Simultaneous planning in transport chain networks is characterized by designing intermodal networks with logistics infrastructure in the form of hubs or intermodal terminals that provide services to the freight. The consideration of services such as transshipment, consolidation/deconsolidation and classification is inherent in hubs, whereas in intermodal terminals the only service provided is transshipment. 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 as logistics support services for the generation of value added to the product, parking, and restaurants, inter alia. Guimarães et al. (2017) is an example of proposals of this type, although in this particular case only transshipment costs are modelled.

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 example, Amaral et al. (2012) do so when evaluating any possible bottlenecks in the network and identifying better routes when diversions are required. Kim et al. (2013) establish capacities to assess network expansion options, and Zhang et al. (2013) also do 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 base network. Both alternatives assess potential sites for the infrastructure on the basis of a given complex. Potential sites are subject to existing transport networks for each mode to be analysed in the case of discrete base networks. Solving models with base networks is supported by the use of IT georeferencing tools that accurately locate location points. These tools are discussed in Section 4.4.

The number of logistics infrastructures to be installed can be modelled as a parameter in a restriction depending on the set of defined scenarios, or by establishing the infrastructure capacity limits that intrinsically define the total number. 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) and Zhang et al. (2015) evaluate different network configurations by defining scenarios subject to different greenhouse gas emission price policies. For the last alternative, Guimarães et al. (2017) propose defining the facility's minimum and maximum capacity. The minimum limit equates to the minimum volume of freight that should be allocated to a facility for it to be included in the network, whereas the maximum limit equates to the maximum volume of freight that can be allocated to the same facility.

Regarding the type of allocation, the inclusion of the concept of scale economy in the development of intermodality generally links only one possible flow allocation to the facilities that are installed, as in the Alumur et al. (2012) and Zhang et al. (2015) proposals, for example. Without distinguishing between types of allocation, transshipment costs and transport costs are evaluated in the link establishment process for each of the analysed modes at the very least. Distances are taken into account for calculating the transport costs. Amaral et al. (2012) and Rothenbächera et al. (2016) apply the concept of Euclidean distance, especially. The distance-cost ratio can be modelled as linear (see e.g., Ishfaq and Sox (2012)) or using the concept of economy of distance, as in Santos et al. (2015). This last study conceives distance of economy as an opportunity to use more efficient transportation modes than road for long distances.

In addition, with respect to the research problem's intermodal efficiency, dispatch service times, transport operational times, service times at the facility, and waiting times at the facility are included in the models. Alumur et al. (2012) apply the triangular inequality concept to transport operational times to comply with service times. Ishfaq and Sox (2012) define a G/G/1 queuing system for operations and waiting at the facility, and Rothenbächera, Drexl, & Irnich (2016) evaluate the possibility of direct or intermodal dispatches with transport operational times. Meanwhile, Kim et al. (2013) and Zhang et al. (2015) only integrate transport operational times, the former to establish improved links that are translated into actions on transport infrastructure and the latter to define the link's transport mode.

Other attributes, such as the speed permitted in the link, freight unit or vehicle capacity, and greenhouse gas emissions are not only included in cost and time calculation but also considered to be constraints on the maximum flow that can be allocated to a link.

Supply Chain Networks

The design of the supply chain network is not only characterized 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 raw material, and (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 consider 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 transshipment logistics, consolidation/deconsolidation, warehousing, and inventory management services and connectivity with different transport modes. This proposal is found in Davidson and Leachman (2012). The strategy employed to respond to seasonal demand is to separate the processing stages for obtaining the final product, with the installation of post-factory specialized intermodal terminals. Xie et al. (2014) apply this strategy and install specialized intermodal terminals for mixing biofuels.

In an evaluation of intermodality as the only strategy for the distribution of multiple products, Kazemi and Szmerekovsky (2015) install distribution centres, whereas Fernandes et al. (2013) install depots. Freight transshipment is carried out at both of these infrastructures but the depots are conceived as areas where there is obligatory warehousing due to the characteristics of the product that is being distributed. However, distribution centres and transitory intermodal points are installed to evaluate the grouping for retail suppliers and inventory cost reduction to address random demand. Alenezi and Darwish (2014) base their model's proposal on these last facilities to perform freight transshipment.

With the exception of the models proposed by Davidson and Leachman (2012), Alenezi and Darwish (2014) and Fernandes et al. (2013), capacity limits are generally set in such a way as to fully exploit the installed infrastructure, with only one option for flow allocation. The first two of these studies do not assume capacity limits as the volumes of the product in the flows do not exceed the infrastructures' real capacity. There are multiple allocations in the last study, as multiple decision-makers are considered at all stages of the chain and, moreover, the installed infrastructures are shared use.

As in transport chain network design, the site for the logistics facility is taken to be a discrete space or a discrete base network in supply chains. However, some of the models used in base networks include the location of transport resources such as maritime docks, railroad stations and the creation of links for specific transportation modes, which results in the expansion of the intermodal transport network.

To establish the link between localized infrastructures, transport distances are taken into account for each of the analysed modes along with transportation costs. Xie et al. (2014) propose a direct relationship between distance and transportation costs, Fernandes et al. (2013) propose that maximum permitted distances be set for each of the required services and transport mode, and Marufuzzaman et al. (2014) use the Hamming concept of distance, for which they define a confidence region that counteracts the unstable behaviour of the model's initial iterations.

As was to be expected, raw material processing times and replenishment times are included in supply chain network design alongside transport operational times and service times. Fernandes et al. (2013) include 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) integrate materials replenishment times, as they model import flows and uncertain demands, which also require the modelling and management of inventories in allocation. However, Alenezi and Darwish (2014) and Xie et al. (2014) consider inventories at the distribution centre and the intermodal terminal intermodal, respectively. Meanwhile, Davidson and Leachman (2012) consider the inventory cycle, inventory in transit, and safety stock. It must be highlighted that the studies that we found on supply chain network design do not evaluate any aspects related to sustainability, and traffic travel speed and freight unit are used as measurement units to assess the link's capacity.

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	+			+			+
Rothenbächera 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	+			+			+

4.3. Modelling facility location-allocation problems

The third analysed aspect refers to the methodological focus for the mathematical formulation that implies location and allocation decisions on intermodal facilities and transport modes. A range of aspects is considered for the study and classification of the proposed formulations. *Focus* refers to the type of mathematical formulation and the solution guideline that represent the research problem and the decisions to be made. *Location decisions* responds to the infrastructures 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 infrastructures 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 mode that operates in a specific link. The chosen transportation mode may be implicit in location or allocation decisions. Depending on the research problem's characteristics and the proposed intermodal network design, other specific important aspects may be involved in the modelling. Some, such as *costs* and *times*, have been addressed in the preceding subsections. However, in the present subsection, they are examined in depth and complemented with aspects specific to each of the models. Table 4 shows the main aspects.

<u>Transport Chain Networks</u>

ILP (integer linear programing), MILP (mixed integer linear programing), MINLP (Mixed integer nonlinear programing) and IP (Integer Programing) are the mathematical programming focuses used to formulate transport chain networks in simultaneous decision making for location, allocation and choice of transport mode. Location decisions are generally represented by a binary variable to determine the use or opening of the facility. However, defining this variable might implicitly entail the decision on the transport mode, as proposed by Alumur et al. (2012), and in other cases, be complemented by another binary variable that establishes a pre-configuration of the facility network, as in Zhang et al. (2013) and Zhang et al. (2015). In addition, if the objective of the decision-makers is focused on reinforcing, redesigning or expanding the network, more than two options can be considered for the location decision, with the decision represented by an integer variable. Kim et al. (2013) apply this strategy to define improvement actions to grow "capacity levels" in relation to the attributes described in Table 3. (previous sub index table). These attributes enable decisions to be taken regarding improvements to the facility and to its physical links depending on the transportation modes being evaluated in the model.

Allocation decisions are represented by binary, integer or continuous variables, which indicates that the type of variable determines the way that network services are designed. Binary variables are used when the decision is subject to defining a single allocation, as in Alumur et al. (2012). These variables are also used to decide on the transport mode, as in Ishfaq and Sox (2012), who represent with this the interest in determining the transport mode that will configure the intermodal combination. Also, in cases where the intermodal focus is only defined among installed infrastructures, binary variables are included based on the transport modes, and the link/s between them, and/or the choice of mode that must be used for the dispatch flow for each origin-destination pair.

Integer variables are generally used when the allocation is determined by the number of freight units or vehicles that travel along the links depending on the chosen transport modes. Rothenbächera et al. (2016) allow this decision to also simultaneously assess the flow of direct dispatches and intermodal dispatches. Santos et al. (2015) complement the decision with a limitation on the maximum number of transshipments. Zhang et al. (2015) use them to determine the transport mode that configures the intermodal network at the lowest cost. Lastly, continuous variables are mainly used to define the quantity or fraction of the total quantity of product that has to flow when selecting a specific link and, as with the other variables, depending on the types of dispatches that model the allocation, whether a single variable is included or more than one is defined. Other complementary decisions are included in the model as auxiliary variables representing effects on intermodality adaptation in network design. Assuming that triangular inequality is satisfied, Alumur et al. (2012) envisage variables of this type to determine the discounts that are produced in journey time and transport cost.

In relation to costs, transportation costs and transshipment costs are considered at the very least. However, 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 infrastructures, costs associated with greenhouse gas emissions, external costs, the cost of expanding the link, expansion costs and costs associated with times and delays. Transportation costs are generally considered by unit of flow and mode. Santos et al. (2015)

model these on the basis of transport vehicle gross weight and distance between terminals. Alumur et al. (2012) and Ishfaq and Sox (2012) include a discount factor to favour the installation of consolidation infrastructures. Transportation costs are also modelled as fractions depending on the cost generated in each section of the network, as can be deduced from Zhang et al. (2013) and Zhang et al. (2015), who not only consider the initial/final costs of the network and the network internal costs, but also model network entry/exit costs.

Although the execution of several logistics activities is considered in the infrastructures, the operational costs modelled mainly correspond to transshipment by transport unit by mode. Exceptionally, Ishfaq and Sox (2012) do not propose them as such, but as the cost generated by the connection between transport modes in relation to the type of service required by the freight in the facility, due to the fact that, apart from transshipment, the freight may require loading/unloading and consolidation/deconsolidation, thus reflecting the different flows inside the facility.

Facility set-up costs and fixed costs are not usually considered in these models due to some seeking the optimization of the existing network and others not being actual decision-makers regarding the investment required for infrastructure installation. Other models envisage only fixed costs and integrate the two concepts into a single cost. 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 and the effects on the environment are relatively recent and are generally focused on greenhouse gas emissions. Several models include these types of costs which, although they are not physical in nature, are used to minimize or restrict the network's contaminating impact and also affect both location, allocation and mode selection decisions, and the execution of the logistics activities carried out in the infrastructures. Zhang et al. (2013) and Zhang et al. (2015) envisage them as described above, while Kim et al. (2013) include these costs in every improvement action required to expand the network. 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) internalize 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) and Zhang et al. (2015) model time costs, although the two proposals differ as to the shares allotted to transport and to product. 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 mode 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 Rothenbächera et al. (2016) and Zhang et al. (2015) for round trip river transport and for rail mode. It is even more interesting to integrate the service times required for each dispatch or set of dispatches in the model—since these are considered to be a combination of transit times and service time in the facility—as they also have an effect on allocation and transport mode decisions. Ishfaq and Sox (2012) also consider 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.

Transport chain intermodal networks are generally proposed as models that are deterministic in type, i.e., every point's demand is known, even by dispatch type.

Supply Chain Networks

MINLP is the mathematical programming focus that to a greater extent defines the proposed supply chain network 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. Fernandes et al. (2013) add in decisions regarding (1) operating the installed infrastructure or not, as when existing facility network optimization is sought in some models, which infrastructure should operate is suggested explicitly, and which should close, implicitly, (2) the quantity of transport resources needed for each of the analysed transport modes if the decision is taken to install and operate the infrastructure, and required to execute the network's intermodal activities, (3) import and/or export volumes of all products and the volume of unsatisfied demand by customer, by product, and by organization. These variables are related to each supply chain's demand characteristics and behaviour. Xie et al. (2014) consider the unsatisfied demand linked to the seasonal behaviour of the modelled products, whereas Marufuzzaman et al. (2014) only consider the total quantity of unsatisfied demand.

As facilities are regarded as factories in these networks, distribution centres and depots are aggregated to the formulation of decisions related to production and capacity planning. Fernandes et al. (2013) and Xie et al. (2014) also decide the quantity of product to be processed in the factories for each of the analysed periods, and Kazemi and Szmerekovsky (2015) decide 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, before or after, to a facility that is already installed involves the modal configuration decision, as 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 that model the flows throughout the network add decision variables that respond to the flows that transit at each stage of the chain using a specific transportation mode. Examples of this are Fernandes et al. (2013), Hajibabai and Ouyang (2013) and Kazemi and Szmerekovsky (2015). Excepting Kazemi and Szmerekovsky (2015), these studies also include other decision variables with which the transport mode is established for flows in links between intermodal infrastructures. Exceptionally, Xie et al. (2014) declare auxiliary variables at the beginning of each period with which they determine the quantity of product to be warehoused 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 are included for 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) divide transport cost between the two, and Alenezi and Darwish (2014) separate out the transport costs for each stage according to the chosen distribution strategy. Fernandes et al. (2013) differentiate costs by period and transport mode. Finally, Hajibabai and Ouyang (2013) incorporate parameters that impact transportation times by increasing the capacity of the links that form the intermodal network.

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

Although a variety of logistics activities are considered for the infrastructures that are installed, operational costs mainly related to intermodal activities such as freight transshipment are not usually modelled. What is distinguished is the installation of transportation resources needed to facilitate the development of these activities. Hajibabai and Ouyang (2013) associate this decision as the cost of expanding infrastructure capacity, whereas Fernandes et al. (2013) associate it separately as the cost of transportation resources. As for other activities, Xie et al. (2014) include 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 product, journey distance and times. Inventory costs are also reflected in the modelling. Alenezi and Darwish (2014) propose the cost of holding inventory associated with distribution centres, and Davidson and Leachman (2012) include safety stock costs and the costs of inventory in transit.

Other costs such as product export and import costs are assumed to compensate for the surplus or lack of the good to comply with demand in a specific period. Fernandes et al. (2013) include these costs and complement them with the inclusion of costs for unsatisfied demand. Xie et al. (2014) only envisage the cost related to unsatisfied demand, whereas, apart from the cost of unsatisfied demand, Marufuzzaman et al. (2014) also include the cost that can be generated by interruptions to network links.

With respect to times, transport times are usually considered in supply chain networks. Davidson and Leachman (2012), Hajibabai and Ouyang (2013), and Xie et al. (2014) include these times in their models. Davidson and Leachman (2012) highlight their randomness and emphasizes in interoceanic times (in the case of the maritime mode) and distribution times in relation to the various distribution strategies that they analyse. These times are also used to set the levels of safety stock in the supply chain to compensate for the effects of uncertain demand, 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) do not envisage the installation of factories, they integrate the processing times of the different products that they distribute through the network in the model.

Supply chain network design model proposals generally consider deterministic demands. In contrast, however, Davidson and Leachman (2012) and Alenezi and Darwish (2014) use risk grouping to model demand uncertainty. The former determine errors in demand forecasts based on normal distribution, while the latter assume 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.

Table 4 Modelling of the intermodal network design

References	16	17	18	19											20			
				A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Transport Chain Networks																		
Amaral et al. (2012)	ILP	A, H	C								+			+				
Rothenbächera et al. (2016)	MIP	A, H	C								+			+		+	+	
Santos et al. (2015)	MIP	A, H	C				+	+			+			+				
Alumur et al. (2012)	MILP	A, E, F	C			+		+		+	+			+	+	+	+	
Guimarães et al. (2017)	MILP	A, H	C					+			+			+				
Ishfaq and Sox (2012)	MINLP	C, H	C			+		+			+			+		+	+	+
Kim et al. (2013)	MINLP	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)	MIP	B, H	C			+		+			+	+		+				

Fernandes et al. (2013)	MILP	A, C, G	C	+		+		+				+		+	+		+
Marufuzzaman et al. (2014)	MILP	A, G, H	D			+					+			+			
Alenezi and Darwish (2014)	MINLP	A, E, H	U			+						+		+		+	
Davidson and Leachman (2012)	MINLP	A, G	U								+	+	+	+	+	+	+
Hajibabai and Ouyang (2013)	MINLP	A, E, H	C			+			+					+			+
Kazemi and Szmerekovsky (2015)	MINLP	A, H	C			+								+			

4.4. Formulation and resolution

Once the main guidelines have been established that characterize the modelling of the intermodal networks being designed, the structure of the mathematical formulation and the resolution procedures used are analysed. Several aspects are included in this key area. Of these, the *function objective* represents the research problem objective and is shown as a function of cost minimization or profit maximization, depending on the chain being analysed. Moreover, it can comprise a single objective or multiple objectives. *Limitations* involves the problem's restrictions. *Periods* refers to the consideration of the time in which the optimization of the objective is planned. *Resolution procedure* corresponds to the set of phases, techniques and relaxation and breakdown methods used to achieve optimization and provide the solution to the proposed research problem. And *IT tool* is the solver used to find the solution to the formulation.

It is important to mention that we do not intend to offer a highly detailed description of the mathematical formulation in this subsection, but rather to highlight the most relevant elements in said formulation and in the resolution procedures used in the simultaneous planning of intermodal facility location-allocation problems.

Table 5 lists the main aspects in the formulation and resolution of the intermodal network design.

<u>Transport Chain Networks</u>

Decision making in transport chain networks has been based on formulations aimed at minimizing costs with multiple objective functions. The exception is Amaral et al. (2012), who propose a mono-objective function to minimize transport flow costs along the network in which transshipment costs at the facility are implicitly assumed. Multi-objective formulations mainly address the sum of the costs described in Table 4 (in the previous section). It should be highlighted that some of these models are formulated on two levels, with the upper level for location decisions and the lower level for flow allocation decisions.

However, some models such as Kim et al. (2013) are specifically directed at times and time frame reductions. In this case, costs associated with delays and deadlines are minimized in order to target a homogenous objective. Meanwhile, Zhang et al. (2013) apply relative weights for each of the proposed objectives as they are different in nature. On another note, and in line with the potential of the transport infrastructures as a source of development, Santos et al. (2015) include government subsidies that incentivize intermodal activity.

The usual limitations that affect problem optimization are related to the number of infrastructures to be installed, allocation among infrastructures, ensuring that flows are carried out through the established intermodal infrastructures or links, maintaining the flow, installation capacity and the links. It is interesting to mention that other elements integrated into the model restrict the formulation with their differentiated perspective. Particular elements that can be cited in this respect are service and operational times, the investment budget, and permitted greenhouse gas emissions. So, limitations to operational and transport times based on the required dispatch times can be found in the Alumur et al. (2012), and Ishfaq and Sox (2012) models. If greenhouse gas emissions and investment budget limitations exist in addition to time restrictions, an intermodal network with multiple objectives can be configured, as it contributes with the sustainability of the environment under analysis and, at the same time, a network is being proposed that conforms to the economic reality of the decision-makers. Kim et al. (2013) include improvement actions connected with proposed network expansion under the previously mentioned limitations. For their part, Zhang et al. (2013) and Zhang et al. (2015) consider greenhouse gas emissions to be subject to a fee for each km travelled and tonne transported depending on the mode by which the freight flows.

Multiple period models are not usually found in transport chain networks. However, the experimentation process may entail running a model in different scenarios with each corresponding to a specific period of time. Amaral et al. (2012) use this strategy to analyse the changes that are produced in network design when different data sets are included for each scenario.

The mathematical complexity required for the formulation of the problems under consideration requires relaxation or breakdown procedures to be applied that enable a solution to be found. Consequently, relaxation procedures can vary from budget rethinks for the model to the inclusion and/or change of decision variables and/or restrictions.

Alumur et al. (2012) limit transport modes to two for the configuration of the network's intermodal focus and define time commitments for dispatches. For this, they reformulate the base model and integrate new decision variables and valid inequalities as restrictions. Rothenbächera et al. (2016) also use valid inequalities as a mechanism to strengthen linear relaxation. Ishfaq and Sox (2012) propose 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 low limit for the original problem's optimal value.

Various approximate solution methods have been proposed to address the problems of simultaneous planning of intermodal facility location and allocation. For example, Kim et al. (2013) propose that the problem be broken down 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) and Zhang et al. (2015) use similar focuses in which the genetic algorithms have been enhanced with more refined operators and strategies. Alumur et al. (2012) solve the coverage problem with simple heuristics and subsequently allocate transport flows by considering the corresponding costs. And Amaral et al. (2012) use a branch and cut algorithm with a processing time-based stop criterion formed around the definition of a GAP.

Other formulations are solved with the application of exact methods. For example, Rothenbächera et al. (2016) use a branch and price and cut that considers the creation 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) obtain results with excessive computational times for a small set of facilities. So, the need arises to consider a taboo search to solve real problems.

A variety of IT tools are used to solve the proposed formulations and compare the performance of the proposed solution procedures. These tools 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.

<u>Supply Chain Networks</u>

As with transport chain networks, decision making in the supply chain has been based on cost minimization and involves multiple objectives. Uniquely, Fernandes et al. (2013) propose maximizing profit for the various supply chain actors. For this, they include in the formulation the contribution margin of each of the decision-makers 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 aspects 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), for example; and order replenishment and placement transport and operation times, as in Davidson and Leachman (2012). Meanwhile, Xie et al. (2014) minimize raw materials purchase costs, production, and warehousing at each stage of the chain, and add a penalty cost for unsatisfied demand.

Also differentiating is the fact that costs related to the network usage traffic level are included in the transport costs. Costs related to passenger flows are being considered in public networks, as proposed by Hajibabai and Ouyang (2013). Also, the interruptions and emergency actions required to fulfil dispatches enable the consideration of transport costs incurred for direct dispatches. Marufuzzaman et al. (2014) link the likelihood of interruptions occurring in intermodal network links to this based on a series of disaster scenarios that enable to analyse the emergency route that minimizes transport cost.

It is not possible to define common limitations set 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 product 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. An example of this can be found 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 chain networks, supply chain networks do not include aspects in the models 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 has been installed, it remains open for all periods, but that the quantities of product to be manufactured, warehoused and distributed, and unsatisfied demand, are subject to the analysed periods. Xie et al. (2014) and Fernandes et al. (2013) propose formulations that include other aspects. The latter also consider 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 the papers by Marufuzzaman et al. (2014), Hajibabai and Ouyang (2013) and Kazemi and Szmerekovsky (2015), respectively.

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) define logical master cuts, optimal Pareto cuts, confidence region, and backpack inequality, defining the primal-dual for the sub-problem. Fernandes et al. (2013) restrict the set of links in the supply chain distribution stage.

Heuristic techniques are used to define the optimal distribution links in the network. Davidson and Leachman (2012) develop a heuristic to determine the location and apply a shortest path algorithm to determine allocation. Despite using the same allocation technique, Kazemi and Szmerekovsky (2015) use geographic location systems such as ArcGIS to make location decisions.

As with the transport chain networks, IT tools are used to code and resolve the formulations, including CPLEX, GAMS, MATLAB, and XpressMp.

Table 5 Formulation and resolution of the intermodal network design

References	21	22	23	24	25 A	25 B	25 C
Transport Chain Networks							
Amaral et al. (2012)	Min	UO	G	U		Branch and cut	CLPEX 11.1 GNU GLPK 4.8
Alumur et al. (2012)	Min	MO	E, F, G	U	Valid inequalities, promises of time	Heuristic	GUROBI 4.5.2
Guimarães et al. (2017)	Min	MO	G				CPLEX 12.6
Ishfaq and Sox (2012)	Min	MO	E, F, G	U	Lower bound, linear relaxation,	Branch and bound, tabu search	BONMIN
Kim et al. (2013)	Min	MO	A, D, G		Bi-level, Big M	Genetic and shortest path algorithm	
Rothenbächera et al. (2016)	Min	MO	G		Valid inequalities, column generation	Branch and bound and price	CPLEX 12.6
Santos et al. (2015)	Min	MO	G				
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	Bi-level, Redundant constraints	Lagrange	MATLAB
Davidson and Leachman (2012)	Min	MO	C, G	U		Heuristic and shortest path algorithm	
Fernandes et al. (2013)	Max	MO	C, G	M		Heuristic	GAMS y CPLEX 12.3
Hajibabai and Ouyang (2013)	Min	MO	G	U	Lagrange	Genetic and traffic assignment algorithm	
Kazemi and Szmerekovsky (2015)	Min	MO	B, G	U	SIG	Shortest path algorithm	GAMS y XpressMp
Marufuzzaman et al. (2014)	Min	MO		U		Benders decomposition	GAMS y CPLEX
Xie et al. (2014)	Min	MO		M			

5. Discussion and further research directions

Current economic processes have turned intermodality into a strategic research area. 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 (Bontekoning et al., 2004; Macharis and

Bontekoning, 2004; Caris et al., 2008; Dekker et al., 2012; Caris et al., 2013; Lam and Gu, 2013; SteadieSeifi et al., 2014; Caris et al., 2014; Rožić et al., 2016; Agamez-Arias and Moyano-Fuentes, 2017) as it analyses the way that the literature addresses simultaneous 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 chain or configuration issues; supply chains also regard it as an effective management option for material flows.

Although this review has analysed documents on all three previously mentioned decisions, their focuses have differed depending on the type of network being modelled. In transport chain networks, aspects 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 determinants. It also needs to be highlighted that the integrating nature of location-allocation problems entails the involvement of other decision-makers; in transport chains, for example, governmental bodies are being included as the main actors, while in supply chains, transport chain actors are being considered passive subjects in decision making.

Road and rail are the most frequent transport modes used in the configuration of both types of intermodal network design. 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 be some of the reasons why it is not considered in the model or only the costs and times related to import and/or export flows being assumed.

With regard to the integrated design of the intermodal network, location decisions do not always entail a decision to build new infrastructures but also to optimize the network of existing facilities. This is more characteristic of transport 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 chain networks, even though infrastructures are proposed that combine a number of different logistics services, it is normal for these to be simplified in the modelling process with only transshipment being considered.

Allocation decisions are mainly determined by transportation costs and times, distances between infrastructures, 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 determine location or allocation, and for this, the existing transport infrastructure in the analysed geographic area is taken into account. Notwithstanding, some proposals have extended the decisions to improving the chosen transport links—transport chains—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.

With respect to modelling, the simultaneous planning of location, allocation and transport mode decisions has mainly focused on MINLP and MILP, in which a set of binary variables predominates which enables both the location and the allocation of facilities to be decided, with the possibility of associating the transport mode to these. However, allocation decisions can also be represented by integer or continuous variables depending on the vehicle or freight unit and product flow, respectively. From the perspective of the transport chain, 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 chains, 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 chains. 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. Emphasizing the latter, it is common for infrastructures to be financed by the network's own actors in supply chains, whereas, to the contrary, investors can be governmental bodies or public-private partnerships in transport chains, depending on the sector and the geographic area analysed. It is not normal for them to be 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, 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 the main objective that prompts design of these networks, more so even than minimizing costs and maximizing 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 aspects of transportation's economics or to ensure that the results of research better fit the needs and the difficulties faced in practice. For example, future studies should stress the development of models directed at optimizing economic processes, integrating 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 budget 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 specialization 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 synchronizing intermodal activities in the network are essential for achieving an affinity of decisions. Assessing these initiatives on the basis of the concepts of synchromodality 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 optimizes 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 for studies to be generated that 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 intermodality. The importance of this lies in the requirements of mainly 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, concern 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 substitution. 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 flows and information flows at 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 intermodal facility location-allocation planning problems require solution techniques that rapidly respond to the custom optimization 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 aspects would establish a differential in the literature and contribute methodological advances in techniques such as multi-staged stochastic programming.

6. Conclusions

This study provides a systematic literature review 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. Key aspects such as (1) the characteristics of the research problem, (2) the particularities of intermodal networks' design, and (3) the proposed solution approaches, among others, are used to classify and analyse the different contributions.

Our analysis confirms that the two dominant research streams in the related literature, namely transportation networks design and supply chain management, focus in different aspects and adopt different approaches to deal with these aspects. These differences extend to the nature of the proposed models and formulations. From the perspective of the transport chain, models aim at capture 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 results of research better fit the needs and the difficulties faced in practice. This review identifies and discusses some of which we consider as the most relevant or urgent ones, and includes emerging concepts of synchromodality and the physical internet is equally appealing for designing and redesigning flexible and dynamic intermodal networks whose maximum installed capacity can be exploited.

Finally, it appears to us 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.

References

Agamez-Arias, A. and Moyano-Fuentes, J. (2017). Intermodal transport in freight distribution: a literature review. *Transport Reviews*, *37*(6), 782-807.

Alenezi, A. and Darwish, M. (2014). Integrated location model with risk pooling and transportation mode selection. *International Journal of Industrial and Systems Engineering*, *16*(2), 200-222.

Alizadeh, M. (2009). Facility location in supply chain. In: Farahani, R., & Hekmatfar, M. (Eds.), *Facility Location: concepts, models, algorithms and case studies, Contributions to management science* (pp. 473-504). Physica-Verlag, Heidelberg.

Alumur, S., and Kara, B. (2008). Network hub location problems: The state of the art. *European Journal of Operational Research*, *190*(1), 1-21.

Alumur, S., Kara, B., and Karasan, O. (2012). Multimodal hub location and hub network design. *Omega 40*(6), 927-939.

Amaral, M., Almeida, M., and Morabito, R. (2012). Um modelo de fluxos e localização de terminais intermodais para escoamento da soja brasileira destinada à exportação. *Gestão & Produção 19*(4), 717-732.

Arabani, A., and Farahani, R. (2012). Facility location dynamics: An overview of classifications and applications. *Computers & Industrial Engineering*, *62*(1), 408-420.

Azarmand, Z., and Jami, E. (2009). Location Allocation Problem. In: Farahani, R., & Hekmatfar, M. (Eds.), *Facility Location: concepts, models, algorithms and case studies, Contributions to management science* (pp. 473-504). Physica-Verlag, Heidelberg.

Bhattacharya, A., Kumar, S., Tiwari, M., and Talluri, S. (2014). An intermodal freight transport system for optimal supply chain logistics. *Transportation Research Part C: Emerging Technologies*, *38*, 73-84.

Bontekoning, Y., Macharis, C., & Trip, J. (2004). Is a new applied transportation research field emerging? –A review of intermodal rail–truck freight transport literature. *Transportation Research Part A: Policy and Practice*, *38*, 1-34.

Bravo, J., & Vidal, J. (2013). Freight transportation function in supply chain optimization models: A critical review of recent trends. *Expert Systems with Applications*, *40*(17), 6742-6757.
Campbell, J., & O'Kelly, M. (2012). Twenty-five years of hub location research. *Transportation Science*, *46*(2), 153-169.
Caris, A., Limbourg, S., Macharis, C., Van Lier, T., & Cools, M. (2014). Integration of inland waterway transport in the intermodal supply chain: a taxonomy of research challenges. *Journal of Transport Geography*, *41*, 126-136.
Caris, A., Macharis, C., & Janssens, G. (2008). Planning problems in Intermodal freight transport: accomplishments and prospects. *Transportation Planning and Technology*, *31*(3), 277-302.
Caris, A., Macharis, C., & Janssens, G. (2013). Decision support in intermodal transport: A new research agenda. *Computers in Industry*, *64*(2), 105-112.
Contreras, I., & Fernández, E. (2012). General network design: A unified view of combined location and network design problems. *European Journal of Operational Research*, *219*(3), 680-697.
Cooper, L. (1963). Location-Allocation Problems. *Operations Research*, *11*(3), 331-343.
Crainic, T. (2000). Service network design in freight transportation. *European Journal of Operational Research*, *122*(2), 272-288.
Crainic, T., & Kim, K. (2007). Intermodal Transportation. In: Barnhart, C., & Laporte, G. (Eds.), Transportation. *Handbooks in Operations Research and Management Science* (pp. 467-537). North Holland, 14.
Crainic, T., Perboli, G., & Rosano, M. (2017). Simulation of intermodal freight transportation systems: a taxonomy. *European Journal of Operational Research*, *270*(2), 401-418.
Davidson, E., & Leachman, R. (2012). Optimizing a multi-strategy port and modal allocation of containerized imports from Asia to the United States. *Journal of Marketing Channels*, *19*(2), 120-140.
Dekker, R., Bloemhof, J., & Mallidis, I. (2012). Operations Research for green logistics – An overview of aspects, issues, contributions and challenges. *European Journal of Operational Research*, *219*(3), 671-679.
Denyer, D., & Tranfield, D. (2009). Producing a literature review. In: Buchanan, D., & Bryman, A., (Eds.) *The Sage Handbook of Organizational Research* (pp. 670-689). SAGE Publications Ltd.
Djafar, W., Amer, Y., & Lee, S. (2015). Models and optimisation techniques on long distribution network: A review. *Procedia Manufacturing*, *2*, 519-526.
Dybskaya, V., & Sverchkov, P. (2017). Designing a rational distribution network for trading companies. *Transport and Telecommunication Journal*, *18*(3), 181-193.
European Conference of Ministers of Transport. (1993). *Terminology on combined transport*. Paris: OECD.
Farahani, R., Hekmatfar, M., Arabani, A., & Nikbakhsh, E. (2013). Hub location problems: a review of models, classification, solution techniques, and applications. *Computers & Industrial Engineering*, *64*(4), 1096-1109.
Felea, M., & Albăstroiu, I. (2013). Defining the concept of supply chain management and its relevance to romanian academics and practitioners. *Anfiteatru Economic*, *15*(33), 74-88.
Fernandes, L., Relvas, S., & Barbosa-Póvoa, A. (2013). Strategic network design of downstream petroleum supply chains: Single versus multi-entity participation. *Chemical Engineering Research and Design*, *91*(8), 1557-1587.
Govindan, K., Fattahi, M., & Keyvanshokooh, E. (2017). Supply chain network design under uncertainty: A comprehensive review and future research directions. *European Journal of Operational Research*, *263*(1), 108-141. https://doi.org/10.1016/j.ejor.2017.04.009

Guimarães, V., Ribeiro, M., Do Forte, V., & Lucena, A. (2017). A location-allocation model for Logistics integration centers. *International Journal of Transport Economics, 44*(2), 273-292.

Hajibabai, L., & Ouyang, Y. (2013). Integrated planning of supply chain networks and multimodal transportation infrastructure expansion: model development and application to the Biofuel industry. *Computer-Aided Civil and Infrastructure Engineering, 28*(4), 247–259.

Ishfaq, R., & Sox, C. (2012). Design of intermodal logistics networks with hub delays. *European Journal of Operational Research, 220*(3), 629–641.

Kazemi, Y., & Szmerekovsky, J. (2015). Modeling downstream petroleum supply chain: The importance of multi-mode transportation to strategic planning planning. *Transportation Research Part E: Logistics and Transportation Review, 83*, 111-125.

Kim, S., Park, M., & Lee, C. (2013). Multimodal freight transportation network design problem for reduction of greenhouse gas emissions. *Transportation Research Record, 2340*(1), 74-83.

Klose, A., & Drexl, A. (2005). Facility location models for distribution system design. *European Journal of Operational Research, 162*(1), 4-29.

Lam, J., & Gu, Y. (2013). Port hinterland intermodal container flow optimisation with green concerns: a literature review and research agenda. *International Journal of Shipping and Transport Logistics, 5*(3), 257-281.

Lambert, D., Cooper, M., & Pagh, J. (1998). Supply chain management: implementation issues and research opportunities. *The International Journal of Logistics Management, 9*(2), 1-20.

Macharis, C., & Bontekoning, Y. (2004). Opportunities for OR in intermodal freight transport research: A review. *European Journal of Operational Research, 153*(2), 400-416.

Marufuzzaman, M., Eksioglu, S., Li, X., & Wang, J. (2014). Analyzing the impact of intermodal-related risk to the design and management of biofuel supply chain. *Transportation Research Part E: Logistics and Transportation Review, 69*, 122-145.

Mathisen, T., & Sandberg, T. (2014). The academic literature on intermodal freight transport. *Transportation Research Procedia, 3*, 611-620.

Mentzer, J., De Witt, W., Keebler, J., Min, S., Nix, N., Smith, C., Zacharia, Z. (2001). Defining supply chain management. *Journal of Business Logistics, 22*(2), 1-25.

Ogryczak, W., Luss, H., Pióro, M., Nace, D., & Tomaszewski, A. (2014). Fair Optimization and Networks: A Survey. *Journal of Applied Mathematics, 2014*, 1-25.

Ostresh, L. (1975). An efficient algorithm for solving the two center Location-Allocation problem. *Journal of Regional Science, 15*(2), 209-216.

Phoon, S., Yap, H., Taha, Z., & Pai, Y. (2017). Interactive solution approach for loop layout problem using virtual reality technology. *International Journal of Advanced Manufacturing Technology, 89*(5-8), 2375-2385.

Rothenbächer, A., Drexl, M., & Irnich, S. (2016). Branch-and-price-and-cut for a service network design and hub location problem. *European Journal of Operational Research, 255*(3), 935–947.

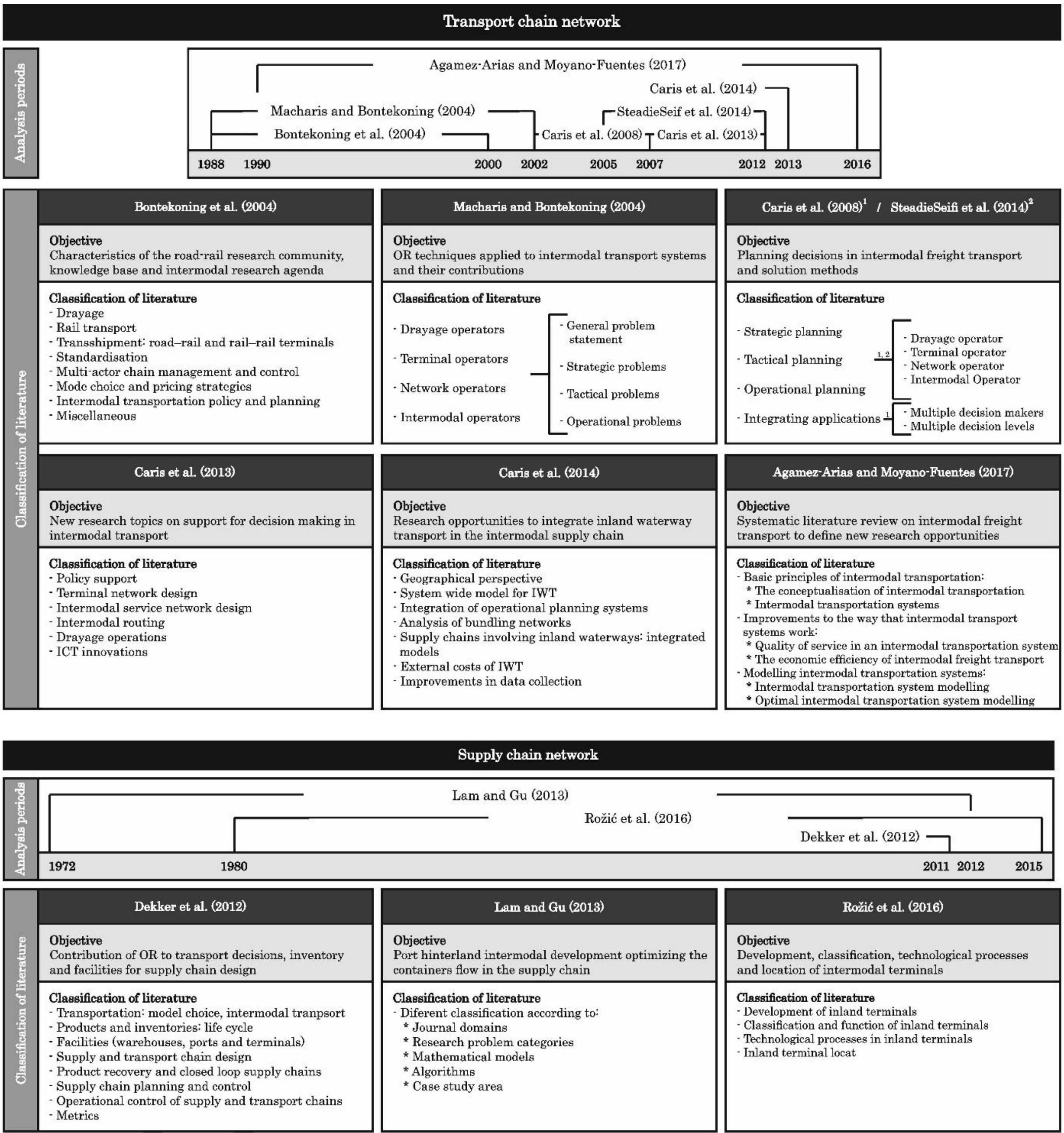
Rožić, T., Rogić, K., & Bajor, I. (2016). Research trends of island terminals: A literature review. *Promet - Traffic & Transportation, 28*(5), 539-548.

Safeer, M., Anbuudayasankar, S., Balkumar, K., & Ganesh, K. (2014). Analyzing transportation and distribution in emergency humanitarian logistics. *Procedia Engineering, 97*, 2248-2258.

Santos, B., Limbourg, S., & Carreira, J. (2015). The impact of transport policies on railroad intermodal freight competitiveness – The case of Belgium. *Transportation Research Part D: Transport and Environment, 34*, 230-244.

Scott, A. (1970). Location-Allocation Systems: A Review. *Geographical Analysis, 2*(2), 95-119.

Sörensen, K., Vanovermeire, C., & Busschaert, S. (2012). Efficient metaheuristics to solve the intermodal terminal location problem. *Computers & Operations Research*, *39*(9), 2079-2090.
SteadieSeifi, M., Dellaert, N., Nuijten, W., Van Woensel, T., & Raoufi, R. (2014). Multimodal freight transportation planning: A literature review. *European Journal of Operational Research*, *233*, 1-15.
Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management*, *14*(3), 207-222.
United Nations Conference on Trade and Development- UNCTAD. (2017). Review of maritime transport. United Nations.
Xie, F., Huang, Y., & Eksioglu, S. (2014). Integrating multimodal transport into cellulosic biofuel supply chain design under feedstock seasonality with a case study based on California. *Bioresource Technology*, *152*, 15-23.
Yamada, T., & Febri, Z. (2015). Freight transport network design using particle swarm optimisation in supply chain–transport supernetwork equilibrium. *Transportation Research Part E: Logistics and Transportation Review*, 164-187.
Zhang, M., Janic, M., & Tavasszy, L. (2015). A freight transport optimization model for integrated network, service, and policy design. *Transportation Research Part E: Logistics and Transportation Review*, 77, 61-76.
Zhang, M., Wiegmans, B., & Tavasszy, L. (2013). Optimization of multimodal networks including environmental costs: A model and findings for transport policy. *Computers in Industry*, *64*(2), 136-145.


Transport chain network
Analysis periods
Agamez-Arias and Moyano-Fuentes (2017)
Caris et al. (2014)
Macharis and Bontekoning (2004)
SteadieSeif et al. (2014)
Bontekoning et al. (2004)
Caris et al. (2008)
Caris et al. (2013)
1988 1990 2000 2002 2005 2007 2012 2013 2016
Classification of literature
Bontekoning et al. (2004)
Objective
Characteristics of the road-rail research community, knowledge base and intermodal research agenda
Classification of literature
- Drayage
- Rail transport
- Transshipment: road–rail and rail–rail terminals
- Standardisation
- Multi-actor chain management and control
- Mode choice and pricing strategies
- Intermodal transportation policy and planning
- Miscellaneous
Macharis and Bontekoning (2004)
Objective
OR techniques applied to intermodal transport systems and their contributions
Classification of literature
- Drayage operators
- Terminal operators
- Network operators
- Intermodal operators
- General problem statement
- Strategic problems
- Tactical problems
- Operational problems
Caris et al. (2008)[1] / SteadieSeifi et al. (2014)[2]
Objective
Planning decisions in intermodal freight transport and solution methods
Classification of literature
- Strategic planning
- Tactical planning
- Operational planning
- Integrating applications
1, 2
- Drayage operator
- Terminal operator
- Network operator
- Intermodal Operator
1
- Multiple decision makers
- Multiple decision levels
Caris et al. (2013)
Objective
New research topics on support for decision making in intermodal transport
Classification of literature
- Policy support
- Terminal network design
- Intermodal service network design
- Intermodal routing
- Drayage operations
- ICT innovations
Caris et al. (2014)
Objective
Research opportunities to integrate inland waterway transport in the intermodal supply chain
Classification of literature
- Geographical perspective
- System wide model for IWT
- Integration of operational planning systems
- Analysis of bundling networks
- Supply chains involving inland waterways: integrated models
- External costs of IWT
- Improvements in data collection
Agamez-Arias and Moyano-Fuentes (2017)
Objective
Systematic literature review on intermodal freight transport to define new research opportunities
Classification of literature
- Basic principles of intermodal transportation:
* The conceptualisation of intermodal transportation
* Intermodal transportation systems
- Improvements to the way that intermodal transport systems work:
* Quality of service in an intermodal transportation system
* The economic efficiency of intermodal freight transport
- Modelling intermodal transportation systems:
* Intermodal transportation system modelling
* Optimal intermodal transportation system modelling
Supply chain network
Analysis periods
Lam and Gu (2013)
Rožić et al. (2016)
Dekker et al. (2012)
1972 1980 2011 2012 2015
Classification of literature
Dekker et al. (2012)
Objective
Contribution of OR to transport decisions, inventory and facilities for supply chain design
Classification of literature
- Transportation: model choice, intermodal tranpsort
- Products and inventories: life cycle
- Facilities (warehouses, ports and terminals)
- Supply and transport chain design
- Product recovery and closed loop supply chains
- Supply chain planning and control
- Operational control of supply and transport chains
- Metrics
Lam and Gu (2013)
Objective
Port hinterland intermodal development optimizing the containers flow in the supply chain
Classification of literature
- Diferent classification according to:
* Journal domains
* Research problem categories
* Mathematical models
* Algorithms
* Case study area
Rožić et al. (2016)
Objective
Development, classification, technological processes and location of intermodal terminals
Classification of literature
- Development of inland terminals
- Classification and function of inland terminals
- Technological processes in inland terminals
- Inland terminal locat

Transport chain network	Network in general	Facilities network	Services network	Transport mode	Load unit	Actors	Resolution techniques
Bontekoning et al. (2004)	ICT Formulation of politics	Optimal design	Optimal design Efficient operations	Type of mode Drayage	Standarization	Drayage Multiple actors Cordinations	OR techniques
Macharis and Bontekoning (2004)	Types of problem	Optimal location Consolidation Operational plan.		Type of vehicle Drayage			Comparison of heuristics
Caris et al. (2008)	Types of problem	Consolidation	Efficient operations	River transport		Drayage Cooperation	Comparison of heuristics
Caris et al. (2013)	Dynamics problem IT innovations	Integrated design	Routing			Drayage	Multi-objectives models
SteadieSeif et al. (2014)	Integrate the plnning levels	Different network topologies				Collaboration	Dynamic and stochastic models Trade-off between objectives
Caris et al. (2014)	Integration with urban networks Intermodality in the supply chain		Synchronized operations	River transport Technology in vehicles		Strategic collaborations	
Agamez-Arias and Moyano-Fuentes (2017)	Design according to geographical area Administrative and legal framework ICT		Efficient operations Specialized staff	Environmental costs		Collaborative planning	

Supply chain network	Network in general	Facilities network	Services network	Transport mode	Load unit	Actors	Resolution techniques
Dekker et al. (2012)	GHG indicators Environment Multicriteria design	Locations Waiting times	Allocation Routing Operational speed	Type of vehicle	Types and sizes		
Lam and Gu (2013)	Multi-objectives models Sustainable Developing countries	Integrate port hinterland	Flow optimization				Hybrid models
Rožić et al. (2016)	Multi-objectives models	Optimal location Integration with dry port	Load distribution Warehouse allocation	River and rail transport Environmental costs			