Emerging trends and developments in multimodal freight transportation: a scientometric analysis using CiteSpace

Full reference: YUAN, S., JIA, P., NOTTEBOOM, T., MA, Q., 2024, Emerging trends and developments in multimodal freight transportation: a scientometric analysis using CiteSpace, *International Journal of Transport Economics*, DOI: 10.19272/202306704005, issn print 0391-8440 · e-issn 1724-2185, Vol. L (3-4), https://www.libraweb.net/articoli3.php?chiave=202306704&rivista=67&articolo=202306704005

Shuang Yuan
School of Maritime Economics and Management of Dalian Maritime University, Dalian, 116026, China
Collaborative Innovation Center for Transport Studies, Dalian Maritime University, Dalian 116026, China
sueyuan@hotmail.com

Peng Jia
School of Maritime Economics and Management of Dalian Maritime University, Dalian, 116026, China
Collaborative Innovation Center for Transport Studies, Dalian Maritime University, Dalian 116026, China
jiapeng@dlmu.edu.cn
ORCID: 0000-0002-3124-3924

Theo Notteboom (corresponding author)
Department of Transport & Regional Economics, Faculty of Business and Economics, University of Antwerp, Antwerp, Belgium
Maritime Institute, Faculty of Law and Criminology, Ghent University, Ghent, Belgium
Faculty of Sciences, Antwerp Maritime Academy, Antwerp, Belgium
theo.notteboom@uantwerpen.be
ORCID: 0000-0003-1203-2571

Qifei Ma
School of Economics and Management, Zhejiang Ocean University,
Zhoushan 316000, China
maqifei@163.com

Abstract: Recent decades have seen a significant increase in studies on multimodal transportation in freight distribution. This study conducts a scientometric analysis of 1297 articles on multimodal freight transportation published from 1996 to 2021, categorizing the evolution into three stages, namely embryonic (1996-2005), fast-paced (2006-2015), and steady development (2016-2021). In light of the increasingly interdisciplinary nature of the research topic, we use CiteSpace to quantitatively conduct multiple content analyses and investigate research trends, including 1) categories; 2) the collaboration among countries, authors, and institutions; 3) highly cited papers and authors; and 4) hot research topics and trends about co-word analysis, co-citation analysis, and clustering in particular. The study intends to deepen insights into the multimodal freight transportation research field through a comprehensive quantitative analysis, delving into the latest research frontiers while delineating the field's longitudinal developments.

Keywords: Multimodal transportation; literature review; scientometrics; CiteSpace; research trends; visual measurement

1. Introduction

1.1. Research scope

The notion of multimodal freight transport

The roots of multimodal freight transport can be traced back to European railway systems, where wooden containers housing personal items of passengers were transported within ports between railway carriages and ocean-going vessels. However, the contemporary concept of multimodal freight transport took shape in the US maritime industry, especially after the advent of standardized containers in the late 1950s (McKenzie, 1989; Levinson, 2016). Multimodal freight transport is thus closely aligned with containerization (Branch,1996; Rodrigue and Notteboom, 2009). It is the development of the transit system beyond the sea-leg on a port-to-port basis to the overland infrastructure. However, multimodal transport covers much more than just container transport[1]. The objective of this paper revolves around multimodal transport within the context of freight transport.

In general terms, multimodalism deals with the movement of goods using various transport modes (Muller, 1995; Beth, 1997). Multimodalism is a characteristic of a transport system that allows at least two transport modes to be used in a door-to-door transport chain. In this sense, the degree of multimodalism is a quality indicator of a transport system. In particular, it is a direct measure of the degree of integration in terms of interconnectivity and interoperability between the different transport modes in one transport system (Vandenberghe, 1997). A corollary to this line of reasoning is that multimodal transport cannot be viewed as a separate mode of transport, but rather as a process aimed at integrating the comparative strengths of existing modes of transport

[1] Several multimodal units can be distinguished: (1) ISO maritime and land containers placed on flat rail wagons (COFC - Container on Flat Car), on container barges or on coastal or seagoing vessels; (2) swapbodies, being the detachable part of a truck that contains the cargo, are only used in a road-rail-road transport chain; (3) Semi-trailers, adapted for combined transport according to UIC standards (Union Internationale des Chemins de Fer), a system commonly referred to as TOFC (Trailer on Flat Car); (4) rolling road systems where entire trucks are driven on adapted flat wagons; (5) semi-trailers which are bimodal units that can be attached to a traditional tractor, but can also be fitted with train undercarriages (bogies) for rail transport.

and technologies. Hayuth added an extra dimension to the above transport system approach by defining multimodalism as the arrangement for through transportation, from shipper to consignee, over the lines of two or more transportation modes - and under through-liability, through-billing and a single through-rate (Hayuth, 1987). Multimodal transport between land and sea, such as road-rail intermodal transportation (Wang, *et al*., 2018; Li, *et al*., 2014; Bergqvist R, 2008; De Miranda Pinto, 2018), water-rail intermodal transport (Feng *et al*., 2014, Yan *et al*., 2020; Yuan and Yu, 2018;), and road-railway-water multimodal transport (Zhang, *et al*., 2019: 2020), are the most frequently used combinations of modes.

For the definitions of intermodal and multimodal transport, it is sufficient that the modes follow each other within the transport chain. The term *combined transport* is narrower and only considers transport where two means of transport are used simultaneously: 'Combined transport involves the carriage of goods in intermodal technical units by rail or waterway as the main mode with an initial or terminal haul by road' (Toubol, 1993:38). The Netherlands Transport Institute defined combined transport as 'Transport in which the original means of transport is transported on or in another means of transport during the standard route' (Nieuwenhuis, 1986:246). In more recent works, combined transport is often defined to be a specific type of intermodal transport, where environmentally friendly transport modes (rail, inland waterways, or short sea) are used for the major part of the journey (ECMT, 1998). The European intermodal freight transportation sector recently introduced a new definition of combined transport: "an intermodal transport operation where the non-road modes of transport carry out more than 50% of the actual distance that the intermodal loading unit is carried. The 50% should change to 60% in 2035 reflecting the anticipated enhancements in terminal density and rail infrastructure development" (UIRR, 2024).

While the use of the terms multimodal and intermodal transport took off in the 1980s, the notions of co-modality and synchromodality are of much more recent date and up to now have mainly been used in a European context. *Co-modality* is a notion introduced by the European Commission (2006) and in principle refers to the use of different modes on their own and in combination to obtain an efficient and sustainable transport chain. However, compared to the other transport concepts (multimodality, intermodality, and combined transport), co-modality rather neglects the aspect of sustainability as unimodal road transport could also achieve the goal of co-modality, namely the highest efficiency (Reis, 2015). The notion of co-modality underlines collaboration between transport modes and replaced the EU's earlier focus on achieving a *modal shift.* The latter notion is more about opposing transport modes one to another to realize a shift from road transport to rail, inland barges, and or shortsea/coastal shipping.

Cooperation among nodes is also at the core of *synchromodal transport*. Haller *et al.* (2015) define synchromodality as an 'evolution of inter- and co-modal transport concepts, where stakeholders of the transport chain actively interact within a cooperative network to plan transport processes flexibly and to be able to switch in real-time between transport modes tailored to available resources'. A key characteristic of the concept is that not one single kind of party is leading in finding and implementing a synchromodal solution. A synchromodal approach assumes that the shipper books a-modally thereby leaving the decision on the mode(s) of transport to be used to logistics service providers. This renders the whole transport system more flexible in terms of mode choice. In addition, synchromodality makes it possible to consolidate consignments of cargo, thus achieving additional efficiency benefits.

In this paper, the general term *multimodal transport* is used to cover all related notions of intermodal, combined, co-modal, and synchromodal transport despite the different nuances between these concepts and the overall ambiguity that might result from this as outlined above and also pinpointed by Reis (2015). Multimodal transport is highly valued by countries worldwide, many of which have implemented policies in the past decades to promote multimodal transport and strengthen their competitive position in the global trade and supply chain landscape. For example, the Fixing America's Surface Transportation (FAST) Act in the US established a National Multimodal Freight Policy that includes national goals to guide decision-making. The US Department of Transport (DOT) developed a National Freight Strategic Plan (NFSP) and a National Multimodal Freight Network (NMFN). In Europe, the European

Commission's Sustainable and Smart Mobility Strategy together with an action plan guides the work in the field of EU transport policy for the period 2021-2024. This strategy lays the foundation for how the EU multimodal transport system can achieve its green and digital transformation and become more resilient to future crises. The objective is to realize a 90% cut in emissions by 2050, delivered by a smart, competitive, safe, accessible, and affordable multimodal transport system (see https://transport.ec.europa.eu/). In China, the Medium and Long-Term Plans for the Development of the Logistics Industry (2014-2020) issued by China's State Council identify multimodal transportation as the most critical among the twelve priority initiatives. There has been an increasing interest in multimodal transportation worldwide due to its broad range of interacting stakeholders, multi-dimensional multi-mode collaborative organization networks, and complex heterogeneous resource scheduling.

Academic interest in multimodal freight transport

The vigorous development of multimodal freight transportation has attracted a plethora of researchers since the 1990s from various disciplines, such as operations research (Wang, *et al*., 2019; Song, *et al*., 2019), economics (Bouchery, *et al*., 2020), management (Rossi, *et al*., 2020), environmental science (Qu, *et al*., 2016), etc., who contribute significantly to related studies from various perspectives including modeling, planning layout, resource integration, transportation management, environmental protection, etc. After decades of development, multimodal freight transportation is increasingly mature in infrastructure construction, transportation modes and nodes (such as seaports and inland terminals), management mechanisms, laws, regulations, and many other aspects. At present, related research seems to mainly focus on network layout, intermodal path optimization, and performance evaluation.

Several reviews have been published on the development and research outcomes of multimodal freight transportation. Several observations can be made concerning existing literature review studies. First, despite the importance of multimodal transport in contemporary supply chain management, literature reviews on the topic are rather scarce, often somewhat outdated, and cover a surprisingly small number of studies. Based on a review of 92 publications solely focusing on rail–truck multimodality, Bontekoning *et al.* (2004) identify the characteristics of the intermodal research community and scientific knowledge base. They argue that multimodal transport is moving to a more mature independent research field which distinguishes it from other transport systems. In a related review paper, Macharis and Bontekoning (2004) argue that intermodal freight transportation research needs different types of operations research models than those applied to unimodal transport. A more recent review work is found in Mathisen and Sandberg (2014) which assesses the historical development of academic research on intermodal freight transport covering only 99 papers. One of the most comprehensive and recent literature review studies is found in Agamez-Arias and Moyano-Fuentes (2017). The authors use a systematic literature review (SLR) methodology to identify the research lines developed in 127 studies in all, to propose a criterion for classifying the literature, and to discuss the empirical evidence that identifies existing interrelationships. Three main lines of research were identified: basic principles of intermodal transport, improvements to the way that intermodal transport systems work, and intermodal transport system modeling.

Second, most literature studies focus on very specific aspects of multimodal transport such as the role of dry ports (see e.g., Roso and Lumsden, 2010; Witte *et al.*, 2019; Miraj *et al.*, 2021), the cost factor in intermodal terminals (Wiegmans and Behdani, 2018), the configuration of intermodal hub networks (Basallo-Triana *et al.*, 2021), or environmental aspects of multimodal transport (e.g., Kreutzberger *et al.*, 2003; Lam and Gu, 2013). Other review papers focus on specific methodological approaches. For example, Crainic *et al.* (2018) propose a new taxonomy to structure relevant literature on intermodal transportation simulation models and applications. The review of Steadie Seifi *et al.* (2014) solely focuses on optimization models.

Third, most of the review studies summarized and analyzed the literature qualitatively. Only a few reviews employed statistical methods to carry out a systematic and detailed quantitative analysis of multimodal freight transport research. The study by Mathisen and Sandberg (2014) is bibliometric. The SLR methodology used in Agamez-Arias and Moyano-Fuentes (2017) relates solely to the procedure for conducting the review. An extensive quantitative analysis of the constructed paper database is lacking. Note that in most review papers, the use of quantitative analysis techniques would not even add a lot of value given the rather small sample size of papers considered (typically less than 100 papers).

1.2. Research objective and contribution

This paper quantitatively analyzes trends and developments in multimodal freight transport over the past quarter century, by presenting a scientometric analysis of no less than 1,297 articles on multimodal freight transportation that were published between 1996 and 2021. The broad scope of this study database makes it possible to undertake a very comprehensive review of the past and current state of research into all aspects of multimodal freight transport. Figure 1 provides an overview of the logical sequence in conducting the literature review. The core collection database of the Web of Science (WoS) is used as a data source. Citespace is used to quantitatively analyze the related literature in the field of multimodal freight transportation. Given the large database considered and the methodological approach based on Citespace, this research overcomes the issues related to existing literature review studies as discussed in the previous section, i.e., their outdated nature, their small sample sizes, their focus on specific research sub-fields of multimodal transport and their lack of quantitative scientometric approaches. The main contribution of this paper to extant research on multimodal freight transportation thus primarily lies in providing an all-inclusive and comprehensive quantitative analysis of longer-term developments in this research area. On top of the structured review of existing literature using Citespace, the development status of multimodal freight transportation as well as key topics and future trends are examined using knowledge maps. The findings provide in-depth insight into past, current, and upcoming research streams and topics.

The work is logically divided into three parts. Part 1 (Section 2) introduces the methodology and database construction process. Part 2 (Section 3.1-3.4) presents a quantitative analysis of the volume and scope of multimodal freight transportation literature, its subjectivity (core authors, institutions, and countries); research fields; and most influential authors and documents. Part 3 (Section 3.5) outlines the characteristics and popular topics of multimodal freight transportation research, as well as recommendations on pertinent and promising research tracks.

< *insert figure 1 about here* >

2. Research methodology

2.1 Data collection and database construction

The initial step entails selecting a comprehensive and reputable bibliographic database that offers wide-ranging access to high-caliber peer-reviewed journal articles. For this study, we employ the Web of Science Core Collection (WoSCC) as our primary data retrieval source. Multimodal, intermodal, co-modal, and the more recent synchromodal transportation are all terms used in the literature and industry (Steadie Seifi *et al.*, 2014). Therefore, the search terms are set as follows: TS (Topic Search) = ("multimodal transport" or "multimodal transportation" or "multimodality" or "intermodal transport" or "intermodal transportation" or "intermodality" or "co-modal transport" or "co-modal transportation" or "co-modality" or "combined transport" or "combined transportation" or "synchromodal transport" or "synchromodal transportation" or "synchromodality").

As demonstrated in Figure 1, a subject search using these keyword terms resulted in 6,367 journal articles published between 1996 and 2021. An initial content assessment of the abstracts of these publications facilitated the exclusion of unrelated fields (such as biology, etc.). This step narrowed down the database to 1,910 articles relevant to the transport sector. In the second step, a more detailed content-based evaluation by the authors enabled the elimination of studies focused on passenger transport. As such, the collection of papers was further reduced to scholarly works dedicated to multimodal freight transport. This dataset, encompassing titles, abstracts, and referenced sources, underwent a rigorous examination aimed at removing duplicates and discarding non-relevant contributions. After a last round of rigorous screening by all authors, a final curated dataset of 1,297 contributions was subsequently transferred to CiteSpace for an in-depth scientometric analysis.

2.2 Knowledge mapping using Citespace

CiteSpace is a powerful scientometric software equipped with several critical features tailored for comprehensive academic analysis:

1. Collaboration Analysis: This sheds light on the intricate web of scholarly collaborations by mapping out networks based on authorship data.
2. Co-citation Analysis: This function enables researchers to assess the frequency with which two works are jointly cited in subsequent publications.
3. Burst Detection: This unique feature identifies sudden upticks in the citation frequency of specific works, highlighting emerging research areas or seminal studies.

With these foundational functionalities at its core, CiteSpace is firmly anchored in a robust citation analysis paradigm. It adeptly merges frequency, co-citation, cluster, and social network analyses to craft enlightening knowledge maps. Such visual representations are instrumental in tracing the progression of disciplinary frontiers, underscoring emergent research topics, and elucidating the intricate relationships between varied research subjects. As a bibliometric tool based on mathematical statistics, CiteSpace has been celebrated for its transparent evaluation of literature trends. Its acclaimed ability to pinpoint core academic themes and trace developmental trajectories is well-evidenced by notable studies (e.g., Chen *et al*., 2012&2014; Liu *et al.*, 2015; Song *et al*., 2016; Koondhar *et al.*, 2021). In this review, capitalizing on its myriad of functionalities, we used CiteSpace.5.8.R3 to meticulously depict the pivotal topics and evolving trends within multimodal freight transportation research.

3 Results and discussion

3.1 Research outputs

The amount of literature published in a particular field may be a straightforward indicator of the amount of information available in that sector, and thus a crucial metric for assessing the state of development of the very field. The number of recovered documents is collated by year to depict the overall growth trend of publications and citations in multimodal transport research over the study period. Overall, the volume of published papers and citations in multimodal transportation has risen throughout the research period, as shown in Figure 2. a. The function curves for the published and cited publications show R^2 values of 0.9358 and 0.9922 respectively. Published multimodal transportation writings follow a quadratic growth model, while cited writings follow an exponential growth model.

According to the growth curve of multimodal transportation research, three stages in the development of multimodal transportation research may be identified:

① ***Embryonic development stage (1996-2005)***, in which the number of publications on multimodal transportation-related research remained low, averaging only 11.2 papers per year. During this stage, North America, Europe, and a few other nations began to enact legislation and rules to encourage multimodal transportation. Some researchers believe that a new transportation research application area is forming as it moves on to a more mature independent research field, despite remaining in the pre-paradigmatic phase (Bontekoning *et al*., 2004).

② ***Fast-paced development stage (2006-2015)***, in which the number of papers published on multimodal transportation-related research demonstrated a tendency for a rapid increase, as illustrated in Figure 2.a, with an average of

52.7 articles per year. By this stage, the number of connected conferences was fast increasing, as illustrated in Figure 2.b which aided the growth of the multimodal transportation field significantly. Particularly, since the launch of China's Belt and Road Initiative (BRI) in 2013, especially the countries along the 'Silk Road Economic Belt' are giving increasing attention to the development of multimodal freight transport. Numerous studies have been published in this phase, precipitating a peak in multimodal transport research.

③ ***Steady development stage (2016 to present)*** in which the number of publications related to multimodal freight transportation has shown an ongoing growth trend. In this stage, countries worldwide have a more thorough grasp of multimodal transportation, having inherited the research findings from the previous two stages. Infrastructure, modes of transportation, management systems, relevant construction standards, and legislative frameworks for multimodal transportation continue to improve. Emerging technologies such as big data and the Internet of Things have ushered in a new era of multimodal transport research.

< insert figure 2 about here >

3.2 Categorical analysis

The articles in the multimodal transport database cover 31 subject categories in the WoS, with the top 10 categories being transportation (638 articles; accounting for 49.19% of the total); engineering (562; 43.33%), operations research/management science (338; 26.06%), business economics (315; 24.29%), computer science (238; 18.35%); environmental sciences/ecology (132; 10.18%), science technology other topics (96; 7.4%), automation control systems (63; 4.86%), mathematics (45; 3.47%), and geography (32; 2.47%). The distribution of subject groups indicates that transportation and engineering were given the utmost attention in the field, followed by operations research/management science, and business economics. Due to their high priority and steady proportion throughout the years, these four subjects are acknowledged as fundamental fields of multimodal transportation research. Additionally, multimodal transportation research has evolved into a more interdisciplinary endeavor over time.

The year-by-year evolution of the distribution of the top 10 subject categories is depicted in Figure 3. During the embryonic stage, the majority of papers were classified as transportation research or engineering. The majority of studies were devoted to modeling and optimization of multimodal or intermodal transportation systems, as well as the implementation of transportation infrastructure. Meanwhile, operations research/management science has sprouted as a result of the operational research models now being employed in this new subject and the modeling challenges that must be solved (Macharis and Bontekoning, 2004). The amount of articles published in operations research/management science, and business economics has exploded during the rapid development stage. It is worth noting that computer science played a significant role in this stage. In the steady development stage, studies related to environmental sciences/ecology, science technology on other topics, and automation control systems are on the rise, as multimodal transportation research grew into a more interdisciplinary subject.

< insert figure 3 about here >

3.3 Collaboration network analysis

3.3.1 Country collaboration network

Figure 4.c presents a knowledge map of international cooperation in multimodal transportation research with 81 nodes, 202 connecting lines, and a network density of 0.0623. The measure network density describes the portion of the potential connections in a network that are actual connections. Typically, the

higher the density of a network, the more powerful its network effects are. The country cooperation network is shaped like two poles and a belt, with China and the US at the poles and European countries constituting the belt. China (denoted by 'People's R China') has contributed 265 articles (Figure 4.a.) with a high betweenness centrality (BC) of 0.24 (Figure 4.b), making it the most prolific contributor. The United States follows with 197 publications and holds the highest BC at 0.34. Betweenness centrality quantifies centrality in a graph based on shortest paths, effectively highlighting the extent to which nodes (in this case, countries) act as intermediaries between others. As depicted in Figure 4.b, the US possesses the highest centrality, suggesting that it is the most interconnected node in the network and holds the most influential position. The UK follows closely, with China and the Netherlands occupying the subsequent tier. Notably, several European nations play a pivotal role in forging links with other countries, as evidenced by their elevated BC values (greater than 0.1, highlighted by the purple circles in Figure 4.c). These nations include the United Kingdom (0.30), the Netherlands (0.25), Germany (0.19), Sweden (0.18), France (0.12), and Australia (0.11). Furthermore, links between the United States and European nations, as visualized on the right side of Figure 4.c, appear denser, more prominent, and more vivid in color compared to those on the left. This implies a higher frequency and earlier collaboration between the US (the right pole) and European nations (the belt) relative to the collaborations involving China (the left pole).

< *insert figures 4.a, 4.b and 4.c about here* >

Table 1 enumerates the publications on multimodal freight transport research by country spanning the period from 1996 to 2021. When cross-referenced with the geographical distribution illustrated in Figure 4.a, it is evident that 14 countries have contributed more than 30 papers each. The United States and China distinctly dominate, while a majority of the other significant contributors are from Europe. Notably, European and American nations together constitute 85.7% of the total publications. Within Europe, the Netherlands emerges prominently with 115 papers, underscoring its pronounced emphasis on logistics research in its open economy. The presence of key seaports, such as Rotterdam and Amsterdam, underlines the nation's imperative for adept multimodal transport solutions, serving as vital conduits to the broader European hinterland.

In general, the number of outputs is correlated with the number of research institutes, the amount of research funding, and the policy focus. Multimodal transportation originated in Europe and the United States. European and American governments have built numerous international hubs at superior geographical locations, such as the Port of Los Angeles, Rotterdam, Antwerp, and Hamburg. These ports have contributed to a prosperous multimodal transport situation, while also promoting exchanges and cooperation between European and American countries. As the biggest contributor as well as a rising star, China proposed the "Belt and Road" initiative in 2013 and listed multimodal transportation as the top of the twelve critical projects issued in China’s Medium and Long-term Plans for the Development of Logistics Industry (2014-2020), which greatly expedited the development of multimodal transport in China.

< *insert table 1 about here* >

3.3.2 Institutional collaboration network

The institutional collaboration network is comprised of 457 institutions and 309 collaboration links between 1996 and 2021. The network in which nodes are not isolated with a frequency greater than two is shown in Figure 5. Network density is merely 0.003 in the collaboration network of institutions. This suggests a relatively loose structure characterized by restricted institutional collaboration centered on stable partnerships. From a network perspective, this fragmented situation results in a clustering of groups around major nodes with very little intergroup communication and cooperation.

< *insert figure 5 about here* >

When considering the number of publications, multimodal transportation research organizations are primarily located in universities with only a handful in scientific research institutes (Table 2). Delft University of Technology (72 publications), Beijing Jiaotong University (59), University of Hasselt (27), Dalian Maritime University (24), and Vrije Universiteit Brussel (23) are the top five universities with the most publications. Among them, Delft University of Technology tops the list with the majority of its research focusing on shipping-related multimodal transportation. It can be seen that the cooperation network of institutions is distributed in groups centered on Delft University of Technology. The connecting lines inside the groups are dense and thicker which means many institutions have established enduring alliances. Meanwhile, those links between groups are thinner and lighter in color, indicating that the cooperation between the groups may just have recently started to establish. Additionally, many institutions in European and American countries began cooperating in the 1990s, while others, particularly in China, thrived after 2008, as indicated by the color of the linkages in Figure 5.

< *insert table 2 about here* >

3.3.3 Author collaboration network

We utilized the 'Author analysis' function in Citespace to obtain the author collaboration network map of multimodal transport authors. To analyze the main relationships, we have retained only the well-established collaborations characterized by interactions between two pairs more than twice as well as involving at least three authors, as shown in Figure 6, where the node size represents the number of papers by an author. A larger node denotes more papers published. Similarly, the connecting lines' thickness represents the strength of the connection between two authors. Its color demonstrates when the cooperation emerged (from cooler to warmer colors as time progresses).

< insert figure 6 about here >

The temporal progression of the collaborative network is discerned through varying tie colors. The darkest purple ties indicate the earliest enduring partnerships, tracing back to 1999. Lighter purple hues mark the nascent phase of collaborations, predominantly seen among European authors. A significant surge in collaborations occurred between 2013 and 2018, a critical period for joint endeavors, denoted by the abundant orange ties. Bright yellow ties depict recent collaborations, with a preponderance linked to Chinese authors, signifying their growing influence in the domain—a trend corroborated by the country-based analysis.

According to the outputs, as shown in Table 3, An Caris, Rudy Negenborn, Cathy Macharis, Bart Wiegmans, and Gerrit Janssens, are the top five most prolific authors in the field of multimodal freight transportation, boasting h-index scores of 36, 52, 63, 34, and 22, respectively. Specifically, An Caris primarily researches multimodal transportation planning and modeling; Rudy Negenborn surpasses the others in terms of the number of publications, with the majority of his research on intermodal freight transportation planning and synchromodal transportation; Cathy Macharis has worked on multimodal transportation for over 15 years and is the main author of *Intermodal Transport in Europe* and *A Decision Support System for Intermodal Transportation Strategy.*

The "stars in starry sky" distribution pattern discerned from Figure 6 is emblematic of a domain where a select group of scholars acts as pivotal nodes or hubs. These hubs, while contributing significantly to the knowledge corpus, also play a pivotal role in fostering and nurturing collaborative networks. Their centrality in the network hints at the gravitational pull they exert, drawing in diverse researchers for collaborative endeavors

Delving deeper into the collaboration landscape, prominent "galaxies" in the collaboration map include the one centered around Rudy Negenborn at Delft University of Technology in the Netherlands. This group emerged as a significant cluster around 2013 and had established a robust network focused on synchromodality by 2017. Another influential cluster is formed by An Caris, Cathy Macharis, and Gerrit Janssens (now an emeritus professor) at the University of Hasselt and Vrije Universiteit Brussel in Belgium. This cluster started to establish cooperation as early as the nascent stage of multimodal transport (1996-2005) and it strengthened in subsequent years. Recently, they have ventured into new collaborations, notably with Tomas, emphasizing synchromodal transportation. The cooperation cluster led by Zhu Xiaoning from Beijing Jiaotong University has carved a niche in sea-rail intermodal transport, positioning itself as an emerging collaborative force. Moreover, an early bird in the collaboration arena was the cooperative network centered around Bart Wiegmans who left academia a few years ago. This network holds the distinction of being the pioneer cooperative group in the multimodal transport sector. Historically, researchers in specific clusters typically had shared geographical or institutional roots, promoting close-knit ties. However, the post-2016 landscape witnessed a paradigm shift, with collaborations now spanning beyond previous geographical and institutional confines. Despite these advancements, collaborations between varied clusters remain a rarity.

< insert table 3 about here >

3.4 Co-citation analysis

3.4.1 Author co-citation analysis

The top 15 significant co-cited authors for multimodal transportation research are presented in Table 4. The merged author co-citation time-zone map is showcased in Figure 7 and contains 903 nodes and 3,073 co-citation links.

< *insert table 4 about here* >

The author's co-citation counts, which indicate the author's influence in the field to some extent, are ranked as follows: Cathy Macharis (with 207 co-citations), Teodor Gabriel Crainic (207), An Caris (164), Maryam Steadie-Seifi (139), and Yvonne Bontekoning (135). On closer inspection, five authors (i.e., Cathy Macharis, Teodor Gabriel Crainic, An Caris, Sabine Limbourg, and Meng Qiang) are among both the top 15 most cited and the top 15 most productive authors. It is noteworthy that Cathy Macharis and An Caris rank in the top three of these two rankings, which effectively makes them the leading scholars in this area.

Meanwhile, nodes with purple rings are recognized as having a high BC and red inner rings indicate citation bursts. The combination of a high citation frequency with a high BC signifies a prominent researcher who has had a significant impact on the growth and advancement of his research area. Teodor Gabriel Crainic (0.12), Yvonne Bontekoning (0.11), and Pierre Arnold (0.10) are the three authors with the highest BC in the top 15 most cited authors, which suggests they can be considered as critical innovation drivers in the field, serving as interdisciplinary bridges between different phases of the research with profound impacts on its development. Particularly, Teodor Gabriel Crainic, the first co-cited author, has the greatest centrality, and bridges operations research and the subject of multimodal transportation. Besides, he is the author of *Intermodal Transportation*, *Handbooks in Operations Research and Management Science* (Volume 14), which has accumulated 655 citations. Furthermore, certain writers have shown citation bursts or fast spikes in citation frequency over a short period. The top five includes Emrah Demir (with a burst strength of 16.58, from 2018 to 2021), Athanasios Ballis (12.04, 2004–2010), Cathy Macharis (10.61, 2009–2012), Vasco Reis (8.87, 2018–2021) and Frank Southworth (8.55, 2004–2014), indicating that the papers they produce are worth tracking for their potential to influence the direction of research.

< *insert figure 7 about here* >

According to the time-zone map, authors with highly co-cited articles showed a peak in 2004. Numerous pioneering scholars in the field had already brought themselves to the fore before the commencement of the rapid development phase. Since 2007, the number of nodes has grown significantly, conforming to both the journal co-citation trends and the research output categories shown in Figure 3. This indicates that research in multimodal freight transportation has become increasingly multidisciplinary.

3.4.2 Document co-citation analysis

The document co-citation map in Figure 8 is based on an examination of the entire collection of the 26,221 academic documents cited in the 1,297 records extracted from the WOS core collection. The most frequently referenced papers are normally recognized as cornerstones for their revolutionary contributions (Chen *et al.*, 2006). Figure 9 presents the network of co-citations and terms, by analyzing the sizes and colors of nodes and linkages, co-citation relationships within cluster members, and common phrases in each cluster.

The top 10 most cited papers are from clusters #3, #2, #0, #1 and #5. The paper entitled “Multimodal Freight Transportation Planning: A Literature Review” by Steadie Seifi *et al.* (2014) is the most cited article in the dataset with 90 co-citations, ranked to cluster#0. It presents a structured overview of the multimodal transportation literature from 2005 onward, focusing on the traditional strategic, tactical, and operational levels of planning, and the relevant models and their developed solution techniques. Another article from #0 is Caris (2013), at the third position, which presents new research themes for multimodal transportation decision-making and identifies the current state of the art and gaps in existing models for each research topic. The summarized current trends in intermodal decision support models include the introduction of environmental concerns, the development of dynamic models, and the growth in innovative applications of Operations Research techniques. Crainic *et al.* (2007), Limbourg *et al.* (2009), and Bontekoning *et al.* (2004), at the fifth, sixth, and seventh positions, respectively, are all from #2 and focus on efficiency, cost minimization, and scheduled service network design in multimodal transport. Demir *et al.* (2016), Li *et al.* (2015), and Fazayeli *et al.* (2018) from #3 consider the routing problem.

< insert figure 8 about here >

< insert figure 9 about here >

3.5 Popular topics and emerging trends

3.5.1 Keywords analysis

The visual analysis of keywords helps mine popular topics as well as keep track of the research frontier transitions of a certain knowledge domain (Yu *et al*., 2017). To obtain further insights into the characteristics of the distinct development stages, we conducted keyword analyses for three time periods: the embryonic (1996-2005), the fast-paced (2006-2015), and the steady (2016-2021) development stages. Table 5 offers the top ten keywords in terms of frequency, whereas Table 6 lists the top ten keywords in terms of centrality in the multimodal freight transportation study area at each stage. The two lists of top ten keywords were thus assessed based on their frequency and centrality.

< insert table 5 about here >

< *insert table 6 about here* >

Embryonic stage (1996-2005)

Figure 10 depicts the network of keywords. Some nodes have purple rings around their outer rims that indicate the high centrality of this field. The network presented is relatively simple and has few cross-links between different colors which means less diversity in research content in different years.

The node “model” is the key study topic in this period with the largest frequency as well as centrality. The majority of research entails the creation of fundamental models, as well as the use of operational research methodologies and mathematical models to deal with multimodal transportation challenges. The terms “terminal”, “container”, “algorithm”, and “rail” are related to "model", along with high frequency and centrality. Extant literature of this period primarily concentrated on the modeling of combined water-rail transportation, combined road-rail transportation, containerized transportation, and terminal allocation. Arnold *et al*. (2004) introduced models to solve the location choice of rail/road terminals for freight transport. To optimize container allocation, Bostel, *et al*., (1998) established a class of models with varying levels of complexity and realism for the initial loading and their reloading after transshipment. Linda *et al*. (1997) built a model for operations planning. It is noticeable that the “integer program” is arguably the most popular model type in this period. The review paper by Macharis and Bontekoning (2004) discusses operations research models in multimodal transportation as well as unsolved issues in model building and points out that multimodal transportation research is emerging as a rising research direction. Aside from these keywords listed above, the nodes “service”, and “policy” show up in both lists when comparing the top ten keywords of frequency and centrality. During this time, multimodal research was embryonic, and so was policy and infrastructural development.

< insert figure 10 about here >

Fast-paced development stage (2006-2015)

Figure 11 illustrates that the keyword network during this stage is substantially more complex with a proliferation in nodes and interlacing lines. It marks the onset of a more diverse phase of multimodal transportation research.

Compared with the preceding stage (1996–2005), the keyword "model" remained stable in terms of frequency owing to the complicated research content connected to multimodal transport networks, whereas its centrality experienced a significant drop. The frequency of the nodes “network” and “system” increased significantly. This indicates that after the first stage of development, networks had been gradually adopted by increasingly interconnected multimodal transportation systems, and research at this point was mostly based on network conditions. The three keywords of “algorithm”, “cost”, and “management” show a high frequency as well as centrality, thereby representing the core vocabularies of this development stage, according to a cross-comparison between Tables 5 and 6. In this stage, the infrastructure of the multimodal transportation network largely reached maturity. The network is composed of multiple nodes, multiple connections, and several modes. Consequently, the research perspective placed a heavy emphasis on network organization and scheduling optimization involving time windows, costs, and environmental factors. “Cost” is a hot issue in this phase, as multimodal transportation was urged to perform in a low-cost, high-quality fashion while also considering the environmental factors ever since the global economic crisis in 2008. Governments of various countries have issued new regulations and tax policies to encourage companies involved in multimodal transportation to be more sustainable. It is worth mentioning that environmental costs were increasingly taken into account later in this period. The review by Steadie Seifi *et al*. (2014) discussed the problems in multimodal transportation planning from traditional strategic, tactical, and operational levels, and presented the relevant models and developed solutions.

< *insert figure 11 about here* >

Steady development stage (2016-2021)

As depicted in Figure 12, a greater number of research nodes and linkages were accessed during this period. The keyword "Model" retained the greatest frequency, followed by "network" and "optimization" with which it is associated. The top ten most common keywords have remained fairly unchanged since the fast-paced development period (2006-2015), demonstrating that multimodal transportation research is still largely oriented toward network and optimization models. However, the list of keywords with a high centrality has changed significantly, highlighting an altered research focus of research content. “Framework”, “road”, “emission”, “accessibility”, “assignment”, “time window”, and “climate” are the keywords that had never been listed before in the top ten in terms of centrality. While reviewing the literature, we observed that multimodal transportation research during this period explored the integration and coordination of logistics, information, and capital chains, as well as the design and optimization of multimodal transportation networks. The adoption of the notion of synchromodality during this period exemplifies the increased focus on integration and coordination. An intermodal transportation system allows the combination of different modes to maximize their relative advantages, improving the efficiency of the multimodal transportation system by changing the decisions made at various levels. For example, Demir *et al.* (2016) proposed the Green Intermodal Service Network Design Problem with Travel Time Uncertainty (GISND-TTU) for multiple commodities mixed offline intermodal routing decisions, while Qu *et al.* (2016) analyzed greenhouse gas emissions in multimodal transportation. In addition, of the creation of information-integrated intelligent platforms for multimodal transportation using big data is becoming a new trendy research topic in multimodal transportation with emerging terms and technologies such as informatization, intelligence, Internet of Things, and big data. For example, Ding (2020) focuses on container intermodal transport coordination, considering a mixed time window and creating an effective electronic platform for information exchange.

< *insert figure 12 about here* >

3.5.2 Emerging trends

To analyze emerging trends in this field, two aspects are examined. First, we provide insights into the cluster network map of multimodal freight transport research by focusing on detailed keyword data. Next, we analyze the most cited references, particularly targeting papers that have generated high citation bursts.

The keyword data cluster diagram portrays the structural changes in research contents that have taken place throughout the decades. Figures 13 to 15 depict the term clusters in this field from 1996 to 2005, 2006 to 2015, and 2016 to 2021 respectively. The Mean Silhouette value is employed to measure the homogeneity of cluster members. The larger this value, the higher the similarity. As shown in Figure 13, the clustering result is rational with a mean Silhouette of over 0.8.

< *insert figure 13 about here* >

< *insert figure 14 about here* >

< *insert figure 15 about here* >

"Model", "large scale optimization", "operational research", "Hotelling's analysis", "nonlinear programming", "elasticity", and "nonlinear programming" are the scale clusters from biggest to smallest from 1996 to 2005. From 2006 to 2015, the terms “flow”, “system”, “time windows”, “GIS”, “seaport”, “mixed integer programming”, “drayage”, and “emission” were used; from 2016 to 2021, the terms “carbon emission”, “public transportation”, “modal shift”, “game theory”, “city logistics”, “event tree analysis”, “strategic group”, “cost”, “hazardous materials”, “modeling, transshipment operation”, “green multimodal transportation”, and “machine learning” were clustered. The development of the clusters demonstrates that multimodal freight transportation research has become increasingly refined over time. The first stage focused on large-scale optimization and the introduction of new methodological approaches. The second stage was mostly concerned with operational planning. As seen in Figure 15, the cluster has become increasingly diverse in recent years.

Higher citation frequency or paper citation frequency can reflect the dynamics of a research field. To explore the latest research trends, we selected the 20 most cited references with the highest citation bursts occurring up to 2021 and analyzed and categorized their topics (Table 7).

< insert table 7 about here >

Upon a comprehensive review of the 20 most cited papers concerning multimodal freight transport, several prominent trends and central themes become apparent. Except for two field reviews, the themes of "environmental issues" and "uncertainty and complexity" are notably prevalent, each being the focus of 6 out of the 20 papers. Notably, Demir (2016) experienced a significant surge in citations for his work, receiving a score of 15.08. There is also a pronounced inclination towards "Optimisation and Advanced Algorithms" as 7 of these papers emphasize this topic. It is worth noting that optimization and algorithms have consistently been salient themes in multimodal transport research, encompassing both operational and network optimization. Moreover, the "synchronization" theme has garnered increased attention, as evidenced by the surge in citations across four scholarly papers. The breadth of the field and its dynamic research trajectories are further underscored by spikes in citations for topics like 'modal shift' and 'behavioral and competitive dynamics', in addition to areas such as 'technology integration' and 'safety and regulation'.

Commencing with the data acquisition of high-citation-burst papers juxtaposed against a rich cluster analysis, a preliminary thematic extraction was conducted. This involved the identification of recurring lexical and thematic motifs, further distilled into coherent thematic groupings based on conceptual congruence. Subsequent cross-validation with citation burst data served to fortify the veracity of these emergent themes. We can conclude the following research directions that have emerged and will likely become popular research topics shortly.

- *Emissions and green multimodal transport*. Carbon emissions and other greenhouse gases contribute significantly to climate change, making it one of the world's most pressing challenges. Furthermore, according to the European Commission (2014), transportation is one of the leading causes of CO_2 emissions. As a result, businesses are looking for alternative transportation choices that will allow them to mitigate the negative effects of road transportation while also improving their distribution systems' economic and environmental performance (Demir *et al*., 2016). Although research on carbon emissions has surged in recent years, its related research is expected to become even more popular in the future considering the current policy push towards the decarbonization of freight transport which is particularly felt in the European Union as evidenced by the Green Deal and associated ‘Fit for 55’ program.
- *Emerging technology convergence.* Emerging technologies such as the Internet of Things (IoT), machine learning, autonomous transport, and artificial intelligence (AI) promise an even brighter future for global supply chain logistics in proposing visions of remotely controlled cargo ships, smart ports, and smart highways, and digital solutions that would make route and modal choice and supply chain integration more efficient, resilient and sustainable. Plotting a course toward the future of multimodal

freight transport requires further advances in these technologies, as well as applying a practical framework for transforming data into action through the development and implementation of data analytics tools and digital platforms that can assist in optimizing cargo bundling, demand forecasting, and synchromodal solutions.

- *Safety, Risks, and Contingencies*. The multimodal transportation network is subject to severe impacts by a variety of factors including extreme weather events and natural disasters, epidemics (e.g., COVID-19), and endogenous factors such as traffic accidents (e.g., the Suez Canal blockage in March 2021). Multimodal transport networks are challenged to become more resilient and to adapt to an environment characterized by a wide range of supply chain disruptions and events. Despite strong growth in research on risk analysis and resilient supply chains since COVID-19 (see e.g. Negri *et al*., 2021; Notteboom *et al*., 2021), there remains a lack of systematic studies on risk assessment, risk mechanisms, and resilience building in multimodal transportation networks. An urgent need for event analysis and risk assessment arises with the increasing customer exception and service quality.
- *Behavioral and Competitive Dynamics.* The clustering around "game theory" betokens a burgeoning interest in deciphering both cooperative and competitive behaviors within the multimodal freight transport ecosystem. This aligns with citation bursts pointing to route choice behaviors and market dynamics.
- *Synchromodality and modal shift.* Efficient coordination in multimodal transportation networks hinges on the seamless integration of processes and interfaces, driven by effective asset deployment and digital data systems. However, research delving into simplifying these interfaces using international standards or optimizing synchronization measures like aligning opening hours and route usage is beginning to emerge but is still very limited. Furthermore, the term "modal shift" indicates an evolving focus on the dynamics of

transitioning between various transport modes. This transition is tightly interwoven with the complexities of synchromodality, emphasizing the need for enhanced digitalization and collaboration among stakeholders, from logistics providers to government agencies.

4. Conclusions

In the past decades, multimodal freight transport research has evolved into a mature research field. This paper presented a scientometric analysis of no less than 1,297 articles on multimodal freight transportation that were published between 1996 and 2021, spread over three development stages. This large publication database formed the basis for a very comprehensive review and quantitative analysis using Citespace of the current state of research into all aspects of multimodal freight transport. The methodological approach followed in this literature review study helped to overcome the limitations of earlier and often outdated review papers in the field. The latter suffered from small sample sizes of reviewed studies, a limited focus on specific research sub-fields of multimodal freight transport, and a lack of quantitative review approaches. This paper contributes to extant literature by having provided an all-inclusive and comprehensive quantitative analysis of longer-term developments in the research area of multimodal freight transport.

We conducted an in-depth bibliometric study using Citespace, an innovative visualization tool. Through the generation of knowledge maps, we identified key subjects and themes, collaboration patterns between authors, institutions, and nations, research disciplines, and hot topics in multimodal freight transportation research.

Overall, we found that the research volume dealing with multimodal freight transportation has grown continuously from 1996 to 2021, thereby going through three distinct phases, i.e., from the embryonic (1996-2005) to the fast-paced (2006-2015) and steady (2016-2021) development stages. Through CiteSpace, we identified that the foundational knowledge and ideas in multimodal freight transportation research are mostly derived from the fields of transportation, engineering, and operations and management science. In terms of contributing countries, institutions, and authors, the United States, China, and several European countries (the Netherlands in particular) are the primary drivers of multimodal transportation research, with Delft University of Technology, Beijing Jiaotong University, Shanghai Maritime University, Dalian Maritime University, and Erasmus University Rotterdam being the major contributing institutions. Furthermore, advanced analytical and mapping tools of Citespace were deployed to provide insights into functional linkages between keywords and cited works and authors, and to generate insight into the complex dynamics in research theme clusters.

This exercise also made it possible to identify the research topics that are likely to be on the rise in the near future, namely emissions and green multimodal transport; emerging technologies; safety, risks, and contingencies; behavioral and competitive dynamics; and synchromodality and modal shift.

The findings of the presented review study may benefit scholars in taking advantage of the most recent research frontiers in multimodal freight transportation by referring to the most relevant publications, journals, and institutions. The research output can also help policymakers and practitioners to identify trends and current and upcoming issues in multimodal freight transport research and consider these when designing multimodal strategies. This analytical endeavor thus provides some sort of compass for academics, policymakers, and industry practitioners, elucidating contemporary trajectories and prospective avenues within multimodal freight transport research.

Acknowledgment

< *not included here for review purposes* >

References

Agamez-Arias, A-d-M., and J. Moyano-Fuentes. (2017). Intermodal Transport in Freight Distribution: A Literature Review. Transport Reviews 37 (6): 782–807. https://doi.org/10.1080/01441647.2017.1297868

Arnold, P., Peters, D., Thomas, I (2004). Modelling a rail/road intermodal transportation system. Transportation Research Part E-Logistics and Transportation Review, 40(3), 0–270. https://doi.org/10.1016/j.tre.2003.08.005

Basallo-Triana, M.J., Vidal-Holguín, C.J., & Bravo-Bastidas, J.J. (2021). Planning and design of intermodal hub networks: A literature review. Computers & Operations Research, 136, 105469. https://doi.org/10.1016/j.cor.2021.105469

Bergqvist, R. (2008). Evaluating road-rail intermodal transport services - a heuristic approach. International Journal of Logistics-Research and Applications, 11, 179-199. https://doi.org/10.1080/13675560701633273

Beth, H.L. (1997). The port's role in intermodal transport: will intermodal transport work in Europe ?, in: Essays in memory of Professor B.N. Metaxas, University of Piraeus, 261-267

Bontekoning, Y.M., Macharis, C., Trip, J.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), 1-34. https://doi.org/10.1016/j.tra.2003.06.001

Bouchery, Y., Woxenius,J., Fransoo, J.C. (2020). Identifying the market areas of port-centric logistics and hinterland intermodal transportation. European Journal of Operational Research, 285(2), 599-611. https://doi.org/10.1016/j.ejor.2020.02.015

Bostel, N., Dejax, P. (1998). Focused Issue on Rail Optimization || Models and Algorithms for Container Allocation Problems on Trains in a Rapid

Transshipment Shunting Yard. Transportation Science, 32(4), 370–379. https://doi.org/10.1287/trsc.32.4.370

Caris, A., Macharis, C., Janssens, G.K. (2008). Planning Problems in Intermodal Freight Transport: Accomplishments and Prospects. Transportation Planning and Technology, 31(3), 277–302. https://doi.org/10.1080/03081060802086397

Caris, A., Macharis, C., Janssens, G. K. (2013). Decision support in intermodal transport: A new research agenda. Computers in Industry, 64(2), 105–112. http://dx.doi.org/10.1016/j.compind.2012.12.001

Chang, TS. (2008). Best routes selection in international intermodal networks. Computers & Operations Research, 35(9), 2877–2891. https://doi.org/10.1016/j.cor.2006.12.025

Chen, CM. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. Journal of the American Society for Information Science and Technology, 57(3), 359–377. https://doi.org/10.1002/asi.20317

Chen, CM., Hu, ZG., Liu, SB., *et al*. (2012). Emerging trends in regenerative medicine: a scientometric analysis in CiteSpace. Expert Opinion on Biological Therapy, 12(5), 593–608. https://doi.org/10.1517/14712598.2012.674507

Chen, CM., Dubin, R., Kim, M.C. (2014). Emerging trends and new developments in regenerative medicine: a scientometric update (2000–2014). Expert Opinion on Biological Therapy, 14(9), 1295–1317. https://doi.org/10.1517/14712598.2014.920813

Crainic, TG., Kim, K. (2007). Intermodal transportation. In C. Barnhart, & G. Laporte (Eds.), Transportation. Handbooks in operations research and management science. 14, 467–537.

Crainic, T.G., Perboli, G., & Rosano, M. (2018). Simulation of intermodal freight transportation systems: a taxonomy. European Journal of Operational Research. 270(2), 401-418.

De Miranda Pinto. (2018). Road-rail intermodal freight transport as a strategy for climate change mitigation. Environmental Development, 25, 100-110. https://doi.org/10.1016/j.envdev.2017.07.005

Demir, E., Burgholzer, W., Hrušovský, M., Arıkan, E., Jammernegg, W., Van Woensel, T. (2016). A green intermodal service network design problem with travel time uncertainty. Transp. Res. Part B Methodol. 2016, 93, 789–807. https://doi.org/10.1016/j.trb.2015.09.007

Ding, LQ. (2020). Multimodal transport information sharing platform with mixed time window constraints based on big data. Journal of Cloud Computing: Advances, Systems and Applications, 9(1), 1-11. https://doi.org/10.1186/s13677-020-0153-8

Elbert, R., Müller, J.P., Rentschler, J.(2020). Tactical network planning and design in multimodal transportation – A systematic literature review. Research in Transportation Business & Management, 35,100462. https://doi.org/10.1016/j.rtbm.2020.100462

ECMT (1998). Report on the Current State of Combined Transport in Europe. European Conference of Ministers of Transport, OECD Publications: Paris.

European Commission (2006). Keep Europe moving – Sustainable mobility for our continent. Mid-term review of the European Commission’s 2001 Transport White Paper [COM(2006)314]. Office for Official Publications of the European Communities, Luxembourg.

Fazayeli, S., Eydi, A., Kamalabadi, I.N. (2018). Location-Routing Problem in Multimodal Transportation Network with Time Windows and Fuzzy Demands: Presenting a Two-Part Genetic Algorithm. Computers & Industrial Engineering, 119(5), 233-246. https://doi.org/10.1016/j.cie.2018.03.041

Feng, X.J., Fan, X.J., Zhang, Y., et al. (2014). Sensitivity Analysis on Key Factors of Sea-Rail Intermodal Transport System of Dry Bulk. Applied Mechanics & Materials. 641, 715-720. https://doi.org/10.4028/www.scientific.net/AMM.641-642.715

Haller, A., Pfoser, S., Putz, L.-M., Schauer, O. (2015). Historical Evolution of Synchromodality: A First Step Towards the Vision of Physical Internet. Proceedings of the Second Physical Internet Conference, 6-8 July, Paris

Hayuth, Y. (1987). Intermodality: concept and practice; structural changes in the ocean freight transport industry, Lloyd's of London Press Ltd: Colchester

Heinold, A., Meisel, F. (2018). Emission rates of intermodal rail/road and road-only transportation in Europe: A comprehensive simulation study. Transportation Research Part D-Transport and Environment. 65(12),421-437. https://doi.org/10.1016/j.trd.2018.09.003

Huang, K.C., Lee, Y.T., Xu, H.R. (2020). A routing and consolidation decision model for containerized air-land intermodal operations. Computers & Industrial Engineering.141,106299. https://doi.org/10.1016/j.cie.2020.106299

Ishfaq, R., Sox, C.R. (2011). Hub location–allocation in intermodal logistic networks. European Journal of Operational Research. 210(2), 213–230. https://doi.org/10.1016/j.ejor.2010.09.017

Janic M (2007). Modelling the full costs of an intermodal and road freight transport network. Transportation Research Part D: Transport and Environment. 12(1), 33–44. https://doi.org/10.1016/j.trd.2006.10.004

Kreutzberger, E., Macharis, C., Vereecken, L., & Woxenius, J. (2003). Is intermodal freight transport more environmentally friendly than all-road freight transport? A review. Proceedings of Nectar Conference, June, no. 7, 13-15.

Koondhar, M. A, Shahbaz, M., Memon, K.A. (2021). A visualization review analysis of the last two decades for environmental Kuznets curve "EKC" based on co-citation analysis theory and pathfinder network scaling algorithms. Environmental Science and Pollution Research 28(13), 16690-16706. https://doi.org/10.1007/s11356-020-12199-5

Lam, J. S. L., & 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.

Lei, K., Zhu, X.N., Hou, J.F. (2016). Modeling and simulation of risk communication in multimodal transportation networks. Journal of Transportation Systems Engineering & Information Technology. 2548(2548),71-80.

Levinson, M. (2016). The box. Princeton University Press.

Lin, C.C., Lin, S.W. (2016). Two-stage approach to the intermodal terminal location problem. Computers & operations research. 67(3): 113-119. https://doi.org/10.1016/j.cor.2015.09.009

Linda, K. N., Edward K. M. (1997). A model for medium-term operations planning in an intermodal rail-truck service. Transportation Research Part A: Policy and Practice. 31(2), 0–107. https://doi.org/10.1016/S0965-8564(96)00016-X

Li, G.Q., Kazuki, T., Masai, M., Daiki, O. (2014). Fundamental Analyses for Constructing Road-rail Intermodal Freight Transport System. Journal of Transportation Systems Engineering & Information Technology.14(06), 1-7. https://doi.org/10.1016/S1570-6672(13)60143-9

Li, J., Yang, B., Zhu, X.L.(2019). Path optimization of green multimodal transportation under mixed uncertainties. Journal of Transportation Systems Engineering & Information Technology.19(04), 13-19.

Li, L., Negenborn, R.R., De Schutter, B. (2015). Intermodal freight transport planning – A receding horizon control approach. Transportation Research Part C: Emerging Technologies. 60(01), 77–95. https://doi.org/10.1016/j.trc.2015.08.002

Liu, ZG., Yin, YM., Liu, WD., *et al.* (2015). Visualizing the intellectual structure and evolution of innovation systems research: a bibliometric analysis. SCIENTOMETRICS. 103(01), 135–158. https://doi.org/10.1007/s11192-014-1517-y

Limbourg, S., Jourquin, B.(2009). Optimal rail-road container terminal locations on the European network. Transportation Research Part E: Logistics and Transportation Review. 45(4),551-563. https://doi.org/10.1016/j.tre.2008.12.003

Macharis, C., Bontekoning, Y.M.(2004). Opportunities for OR in intermodal freight transport research: A review. European Journal of Operational Research. 153(2), 400–416. https://doi.org/10.1016/S0377-2217(03)00161-9

Mostert, M., Caris, A., Limbourg, S. (2017). Road and intermodal transport performance: the impact of operational costs and air pollution external costs. Research in Transportation Business & Management. 23,75–85. https://doi.org/10.1016/j.rtbm.2017.02.004

McKenzie, D.R., North, M.C., Smith, D. S. (1989). Intermodal Transportation: The Whole Story. Omaha, NE, USA: Simmons-Boardman. ISBN 0911382097.

Miraj, P., Berawi, M.A., Zagloel, T.Y., Sari, M. and Saroji, G., 2021. Research trend of dry port studies: a two-decade systematic review. Maritime Policy & Management. 48(4), 563-582. https://doi.org/10.1080/03088839.2020.1798031

Negri, M., Cagno, E., Colicchia, C. and Sarkis, J. (2021). Integrating sustainability and resilience in the supply chain: A systematic literature review and a research agenda. Business Strategy and the environment. 30(7), 2858-2886. https://doi.org/10.1002/bse.2776

Nieuwenhuis, G.J. (1986). Het hoe en waarom van gecombineerd rail-wegvervoer. Tijdschrift voor Vervoerswetenschap. 22(3), 244-257

Notteboom, T., Pallis, T., Rodrigue, J.P. (2021). Disruptions and resilience in global container shipping and ports: the COVID-19 pandemic versus the 2008–2009 financial crisis. Maritime Economics & Logistics. 23(2), 179-210. https://doi.org/10.1057/s41278-020-00180-5

Qu Y, Bektas T, Bennell J. (2016) Sustainability SI: multimode multicommodity network design model for intermodal freight transportation with transfer and emission costs. Networks and Spatial Economics. 16(1), 303-329. https://doi.org/10.1016/j.rtbm.2017.02.004

Reis, V. (2015). Should we keep on renaming a+ 35-year-old baby?. Journal of Transport Geography. 46, 173-179.

Rodrigue, J.P., Notteboom, T. (2009). The geography of containerization: half a century of revolution, adaptation and diffusion. GeoJournal. 74(1), 1-5.

Roso, V., Lumsden, K. (2010). A review of dry ports. Maritime Economics and Logistics. 12 (2), 196–213. https://doi.org/10.1057/mel.2010.5

Rossi, T., Pozzi, R., Pirovano, G., et al. (2020) .A new logistics model for the increasing economic sustainability of perishable food supply chains through intermodal transportation. International Journal of Logistics Research and Applications. 24(4), 346-363. https://doi.org/10.1080/13675567.2020.1758047

Soldi, R. (2001). White Paper on European transport policy for 2010: time to decide. International Journal of Bioelectromagnetism, 10(1): 52-55.

Song, Z., Tang, W., Zhao, R. (2019). A simple game theoretical analysis for incentivizing multi-modal transportation in freight supply chains. European Journal of Operational Research. 283(1), 152-165. https://doi.org/10.1016/j.ejor.2019.10.048

Song, J.B., Zhang, H.L., Dong, W.L. (2016). A review of emerging trends in global PPP research: analysis and visualization. Scientometrics. 107(3), 1111-1147. https://doi.org/10.1007/s11192-016-1918-1

Steadie Seifi, M., Dellaert, N.P., Nuijten, W., Van Woensel, T., Raoufi, R. (2014). Multimodal freight transportation planning: A literature review. European Journal of Operational Research, 233(1), 1–15. https://doi.org/10.1016/j.ejor.2013.06.055

Toubol, A. (1993). Possibilities and limitations in combined transport, ECMT, Round Table 91, Paris, 33-62

UIRR (2024). Combined transport operation: a new definition. Press Release, International Union for Road-Rail Combined Transport (UIRR), Brussels, 27 February 2024. https://mailchi.mp/5be90094f598/uirr-press-release-european-freight-transport-needs-to-go-on-a-low-carb-diet-14150922?e=6024e520d0

UNECE (2009). Illustrated glossary for transport statistics. ISBN: 978-92-79-17082-9.

Vandenberghe, K. (1997). The Commission's Intermodal Transport Policy: a systems approach to transport, European Commission DGVII, ESTI conference, Brussel

Wang, Q.Z., Chen, J.M., Tseng, M.L., et al. (2019). Modelling green multimodal transport route performance with Witness simulation software. Journal of Cleaner Production. 48,119245. https://doi.org/10.1016/j.jclepro.2019.119245

Wang, R., Yang, K., Yang, L.X., Gao, Z.Y. (2018). Modeling and optimization of a road–rail intermodal transport system under uncertain information. Engineering Applications of Artificial Intelligence. 72, 423-436. https://doi.org/10.1016/j.jclepro.2019.119245

Wiegmans, B., Behdani, B. (2018). A review and analysis of the investment in, and cost structure of, intermodal rail terminals. Transport Reviews, 38(1), 33-51. https://doi.org/10.1080/01441647.2017.1297867

Witte, P., Wiegmans, B., Ng, A.K. (2019). A critical review on the evolution and development of inland port research. Journal of Transport Geography. 74, 53–61. https://doi.org/10.1016/j.jtrangeo.2018.11.001

Yan,B., Zhu,X., Lee, D H., et al. (2020). Transshipment Operations Optimization of Sea-rail Intermodal Container in Seaport Rail Terminals. Computers & Industrial Engineering. 141,106296 https://doi.org/10.1016/j.cie.2020.106296

Yang,Y., Zhu, X., Haghani, A.(2019). Multiple Equipment Integrated Scheduling and Storage Space Allocation in Rail–Water Intermodal Container Terminals

Considering Energy Efficiency. Transportation Research Record: Journal of the Transportation Research Board. 2673, 199-209. https://doi.org/10.1177/0361198118825474

Yu, D.J., Xu, Z.S., Pedrycz, W., Wang, W.R., 2017. Information sciences 1968–2016: a retrospective analysis with text mining and bibliometric. Inform. Sci. 418–419, 619–634. https://doi.org/10.1016/j.ins.2017.08.031

Yuan,Y., Yu, J. (2018). Locating transit hubs in a multi-modal transportation network: A cluster-based optimization approach. Transportation Research Part E Logistics & Transportation Review.114, 85-103. https://doi.org/10.1016/j.tre.2018.03.008

Zhang, W.Y., Wang, X.F., Yang, K. (2019). Incentive Contract Design for the Water-Rail-Road Intermodal Transportation with Travel Time Uncertainty: A Stackelberg Game Approach. Entropy. 21, e21020161. https://doi.org/10.3390/e21020161

Zhang, W.Y., Wang, X.F., Yang, K. (2020). Uncertain multi-objective optimization for the water–rail–road intermodal transport system with consideration of hub operation process using a memetic algorithm. Soft Computing. 24(5), 3695-3709. https://doi.org/10.1007/s00500-019-04137-6

Zhao,Y., Xue, Q., Zhang, X.(2018). Stochastic Empty Container Repositioning Problem with CO2 Emission Considerations for an Intermodal Transportation System. Sustainability. 10(11): 4211. https://doi.org/10.3390/su10114211

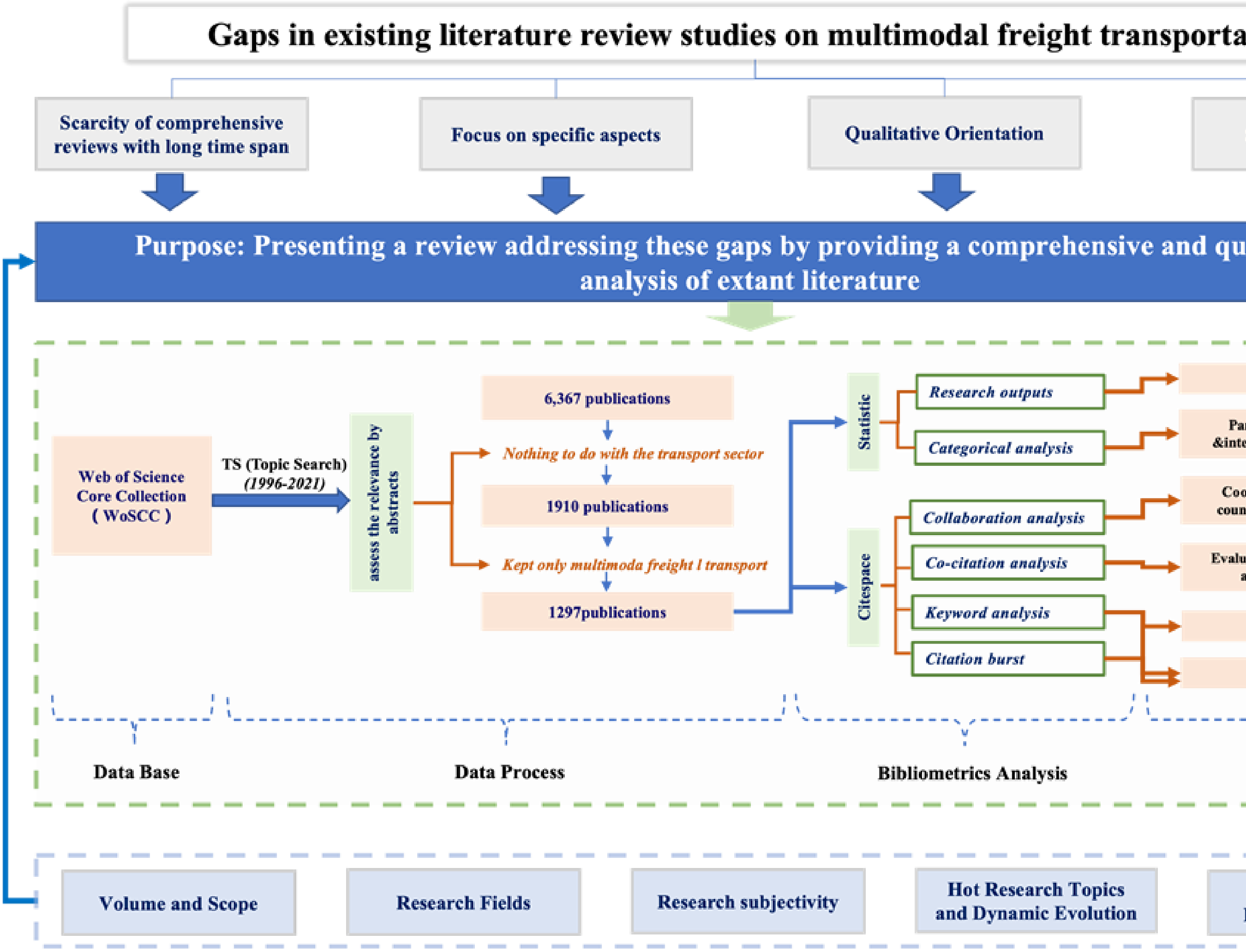

Figure 1. Flowchart of adopted research methodology

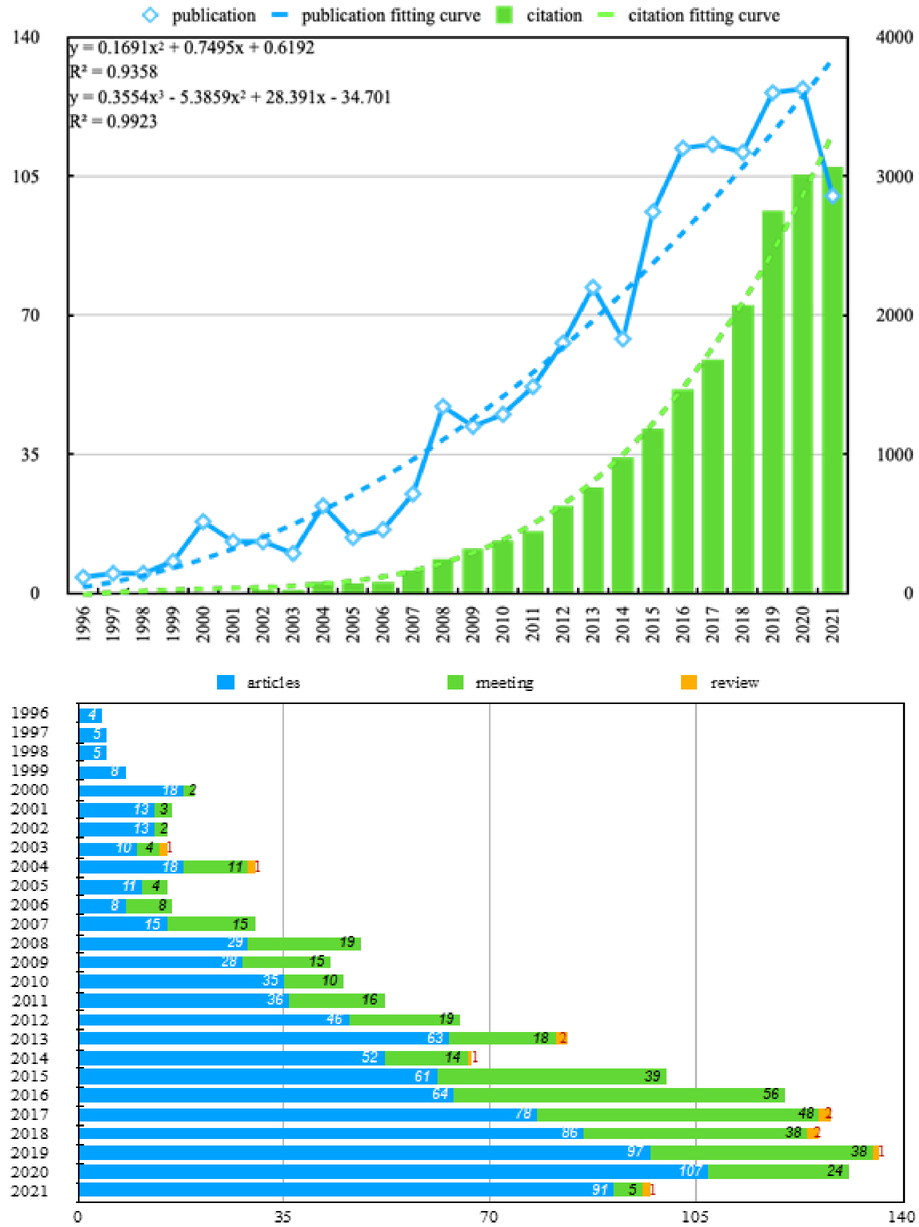

Figure 2. Research output. Fig2.a (top): trend of volumes and citations of published papers; Fig2.b (bottom): document types of published papers.

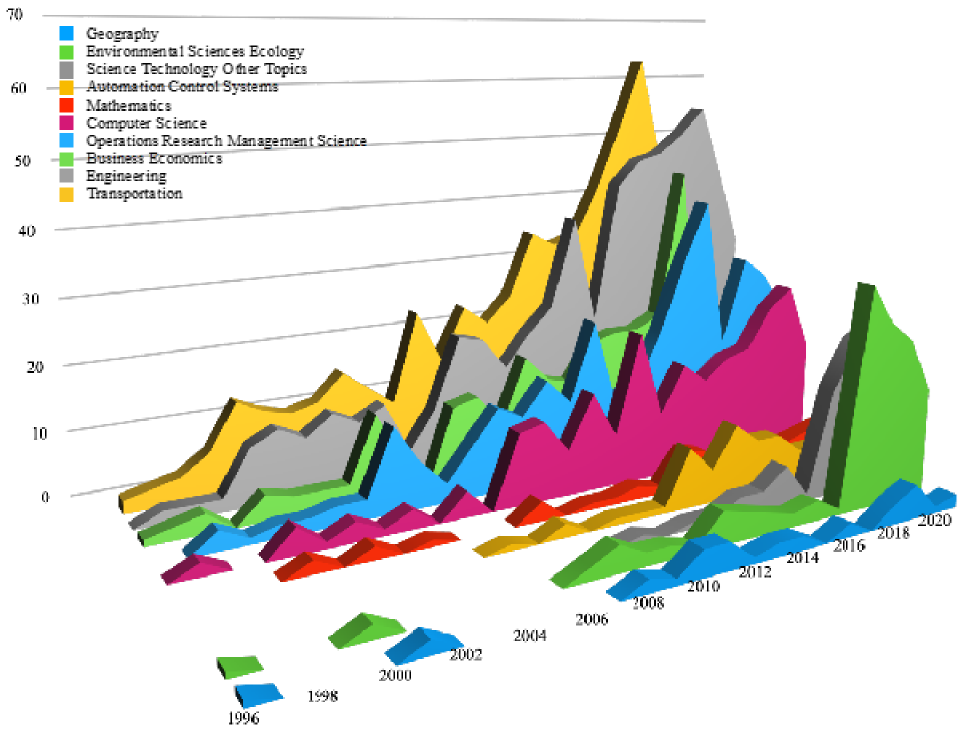

Figure 3. Top 10 subject categories in multimodal freight transportation and their amounts of outputs by year (1996-2021)

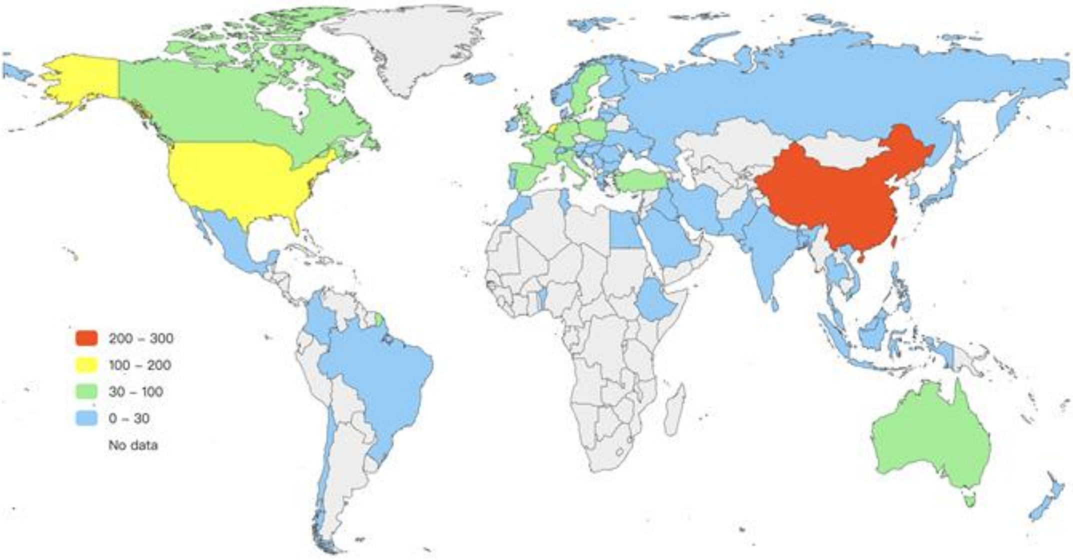

Fig 4.a. Number of publications on multimodal freight transportation between 1996 and 2021, per country

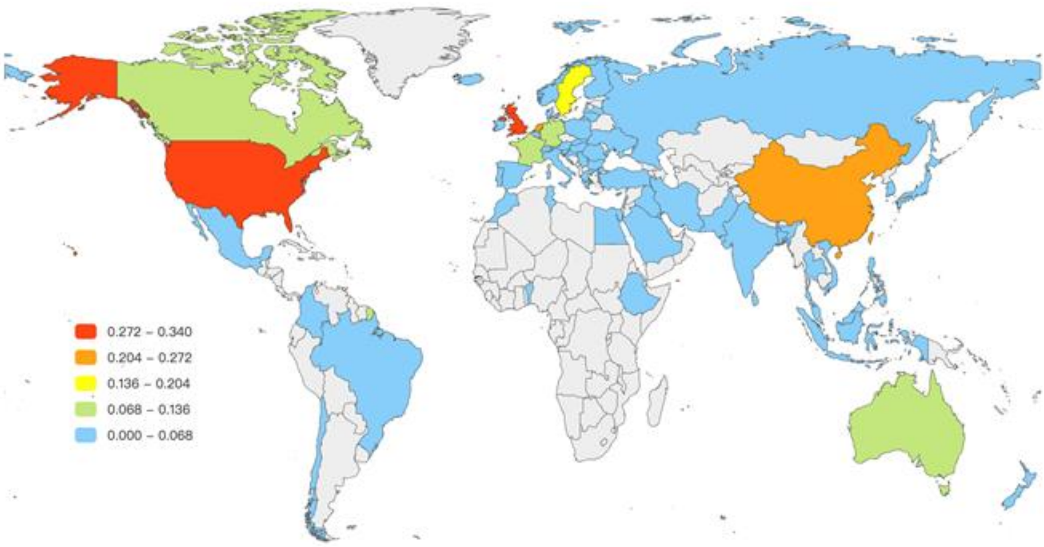

Fig 4.b. Betweenness centrality of individual countries

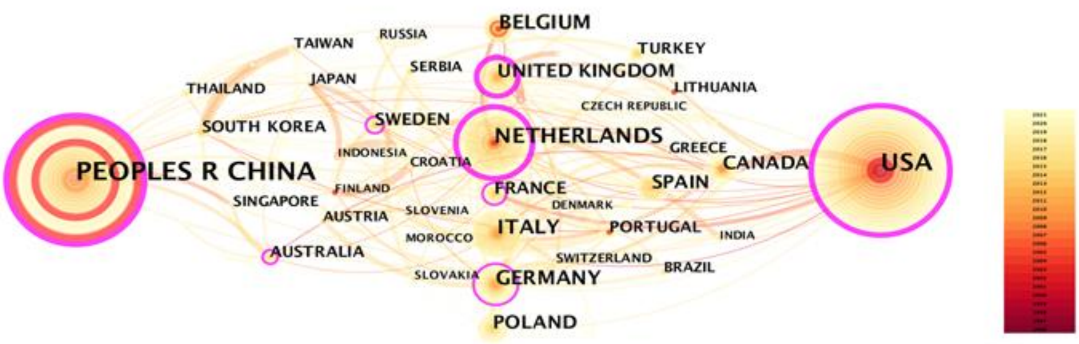

Figure 4.c. Knowledge map of country collaboration in multimodal freight transportation research. . Note: Purple circles represent a centrality over 0.1; red circles represent a burst in this year.

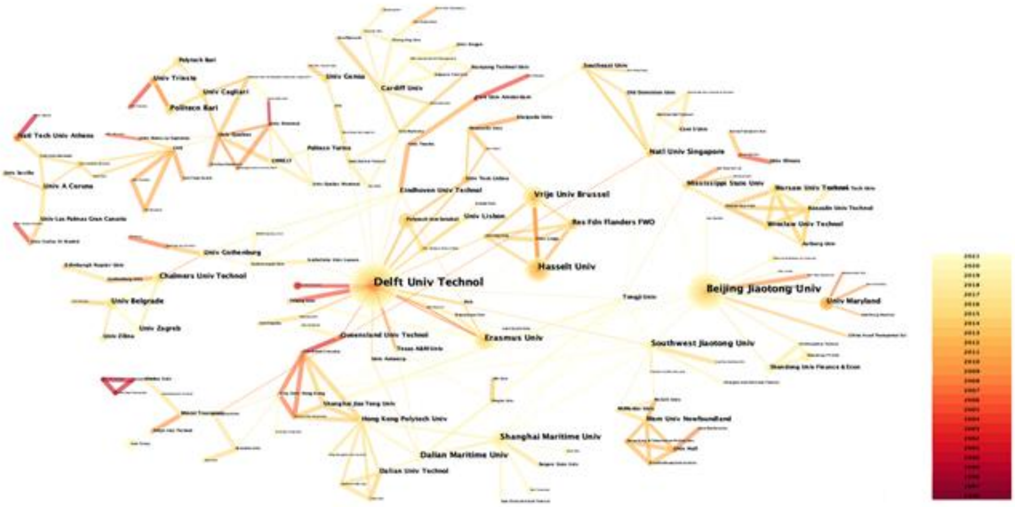

Figure 5. Collaboration map of institutions in multimodal freight transportation research including a color indication of the years involved

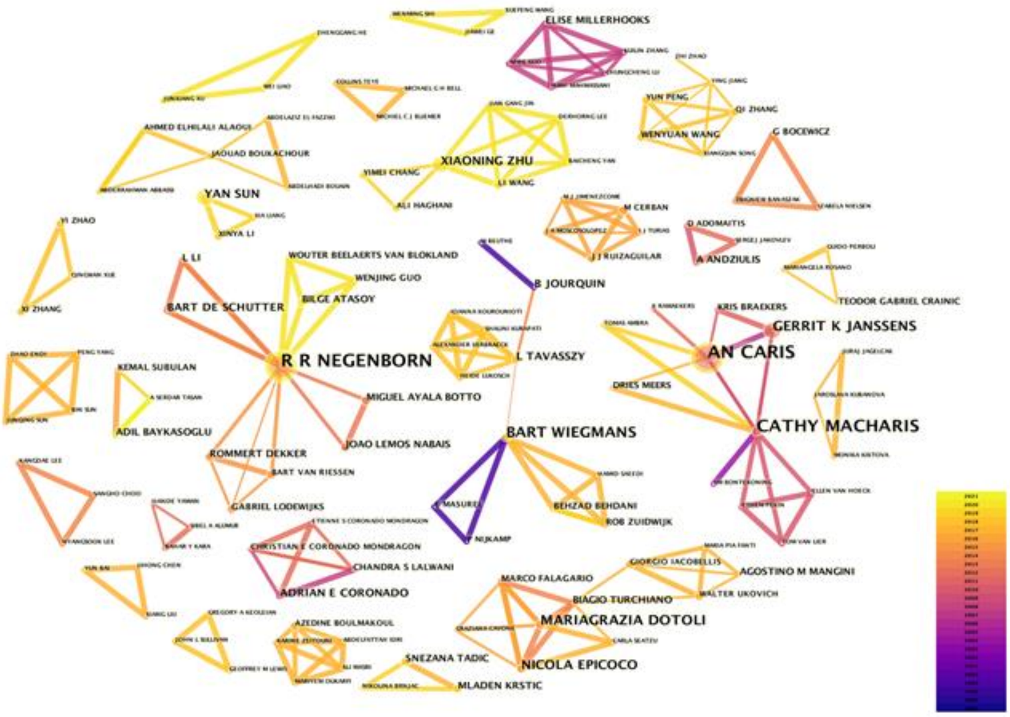

Figure 6. Collaboration map of authors in the field of multimodal freight transportation research including a color indication of the years involved

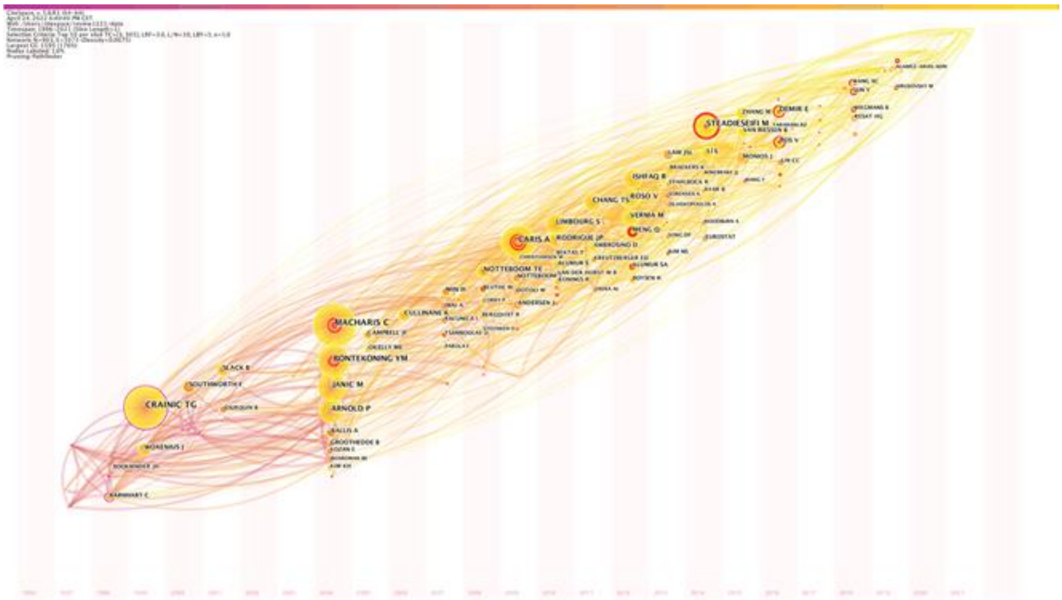

Figure 7. Timezone view of co-cited authors

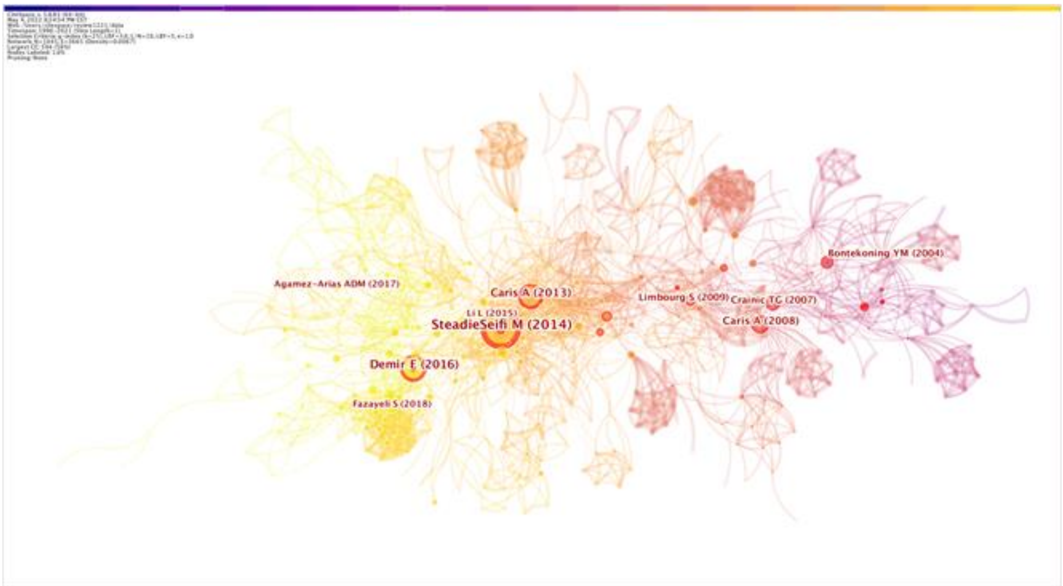

Figure 8. Knowledge map of document co-citation.

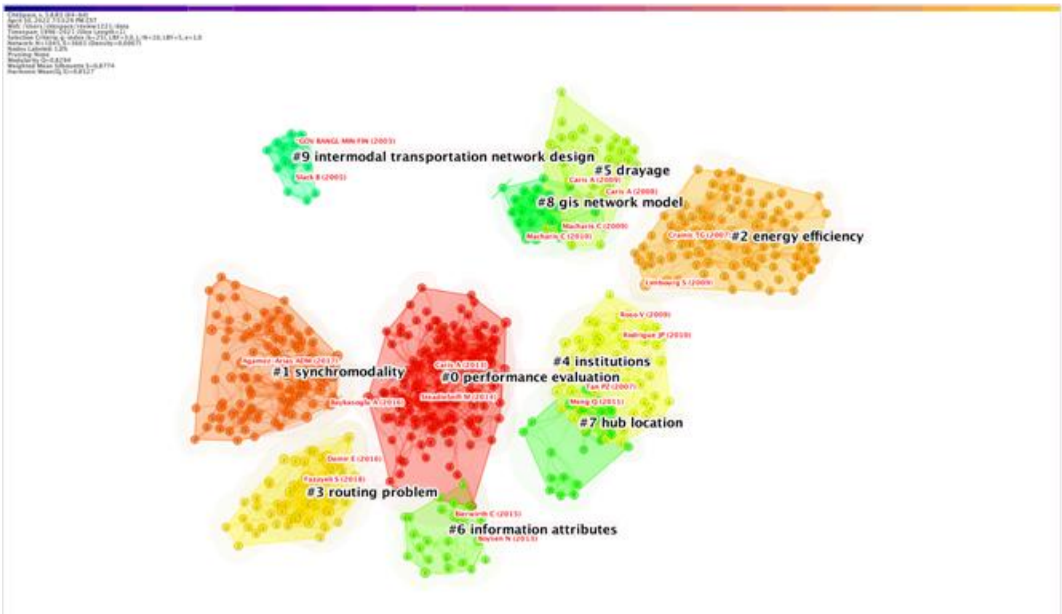

Figure 9. Cluster view of the document co-citations.

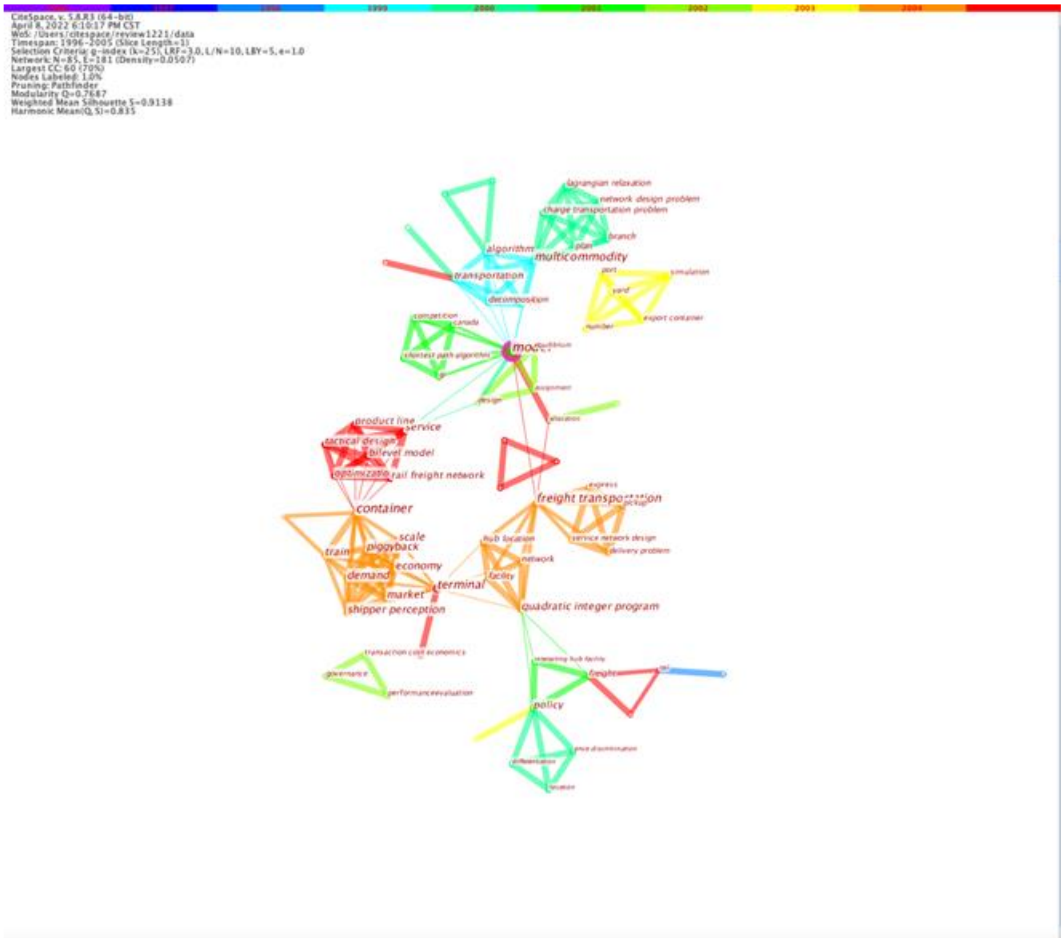

Figure 10. Keyword network map of multimodal freight transport research in the embryonic stage (1996-2005).

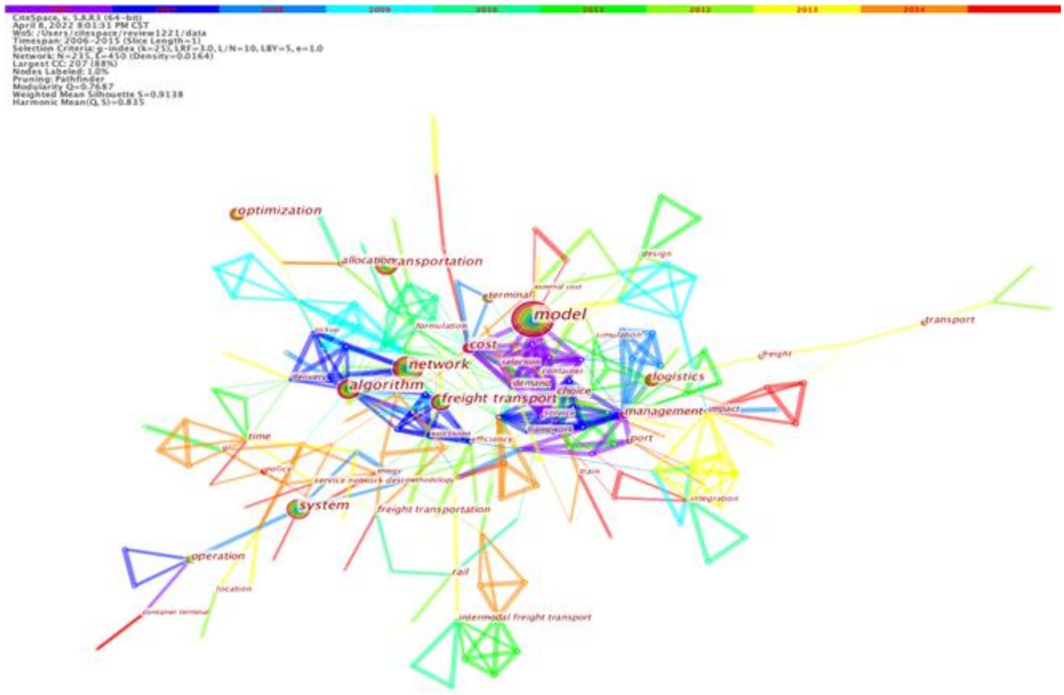

Figure 11. Keyword network map of multimodal freight transport research from 2006 to 2015.

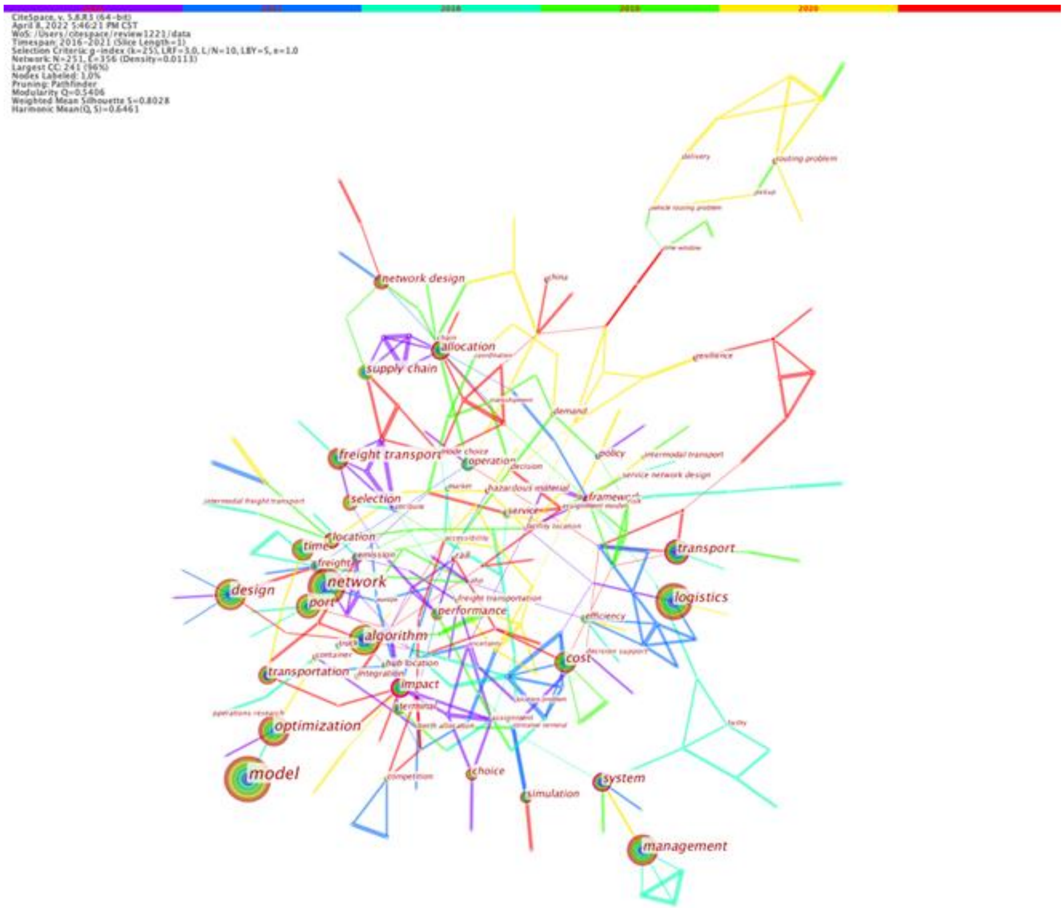

Figure 12. Keyword network map of multimodal freight transport research from 2016 to 2021.

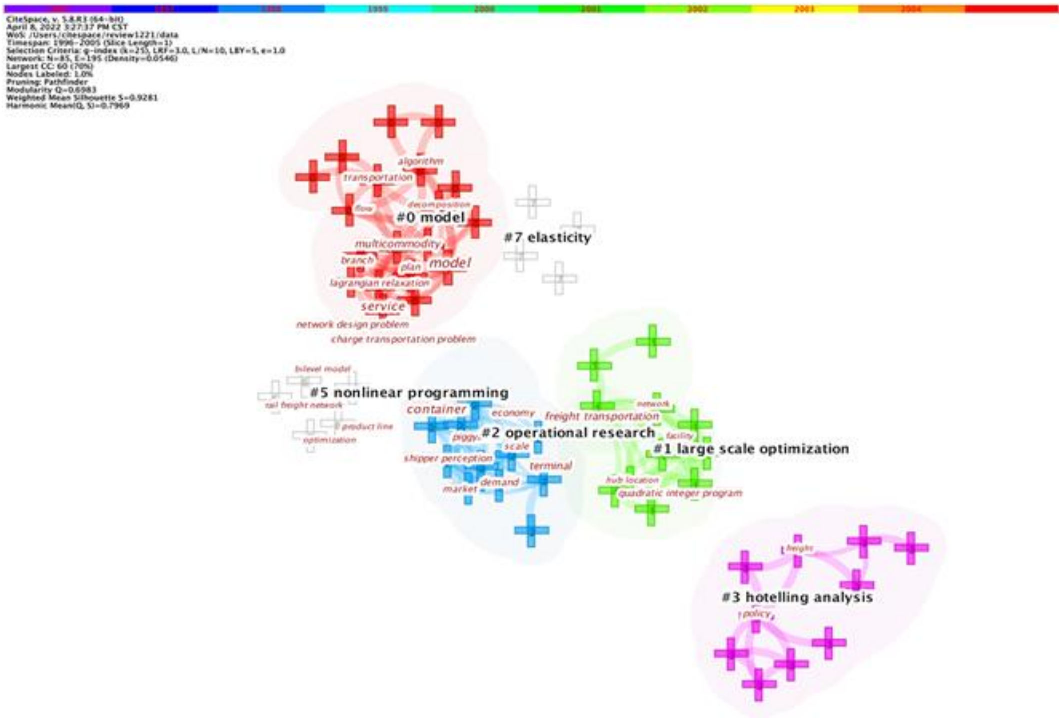

Figure 13. Cluster network map of multimodal freight transport research in the embryonic development stage (1996-2005)

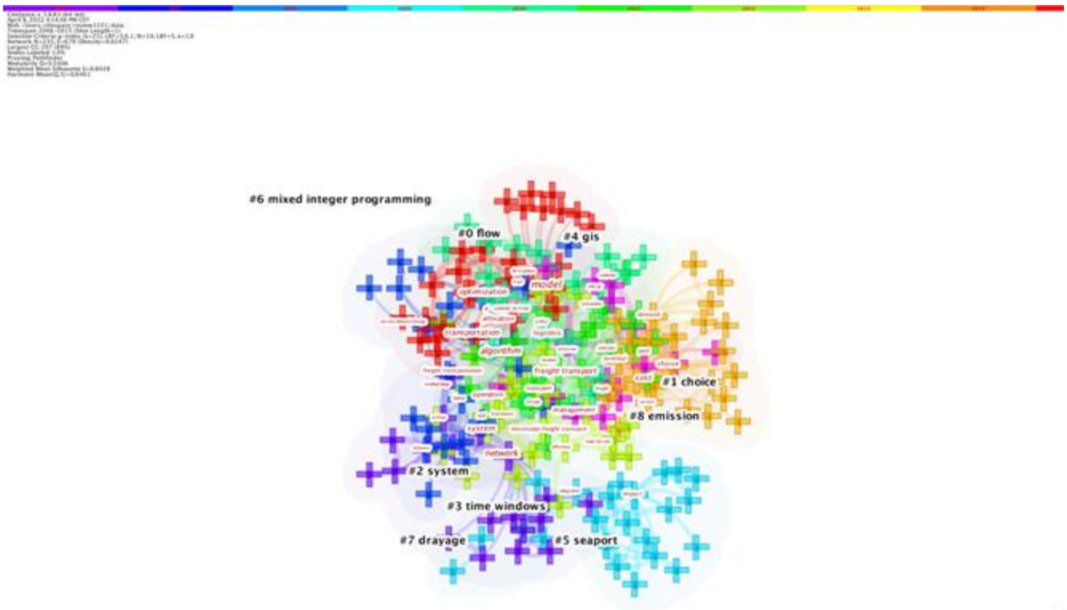

Figure 14. Cluster network map of multimodal freight transport research in the fast-paced development stage (2006-2015)

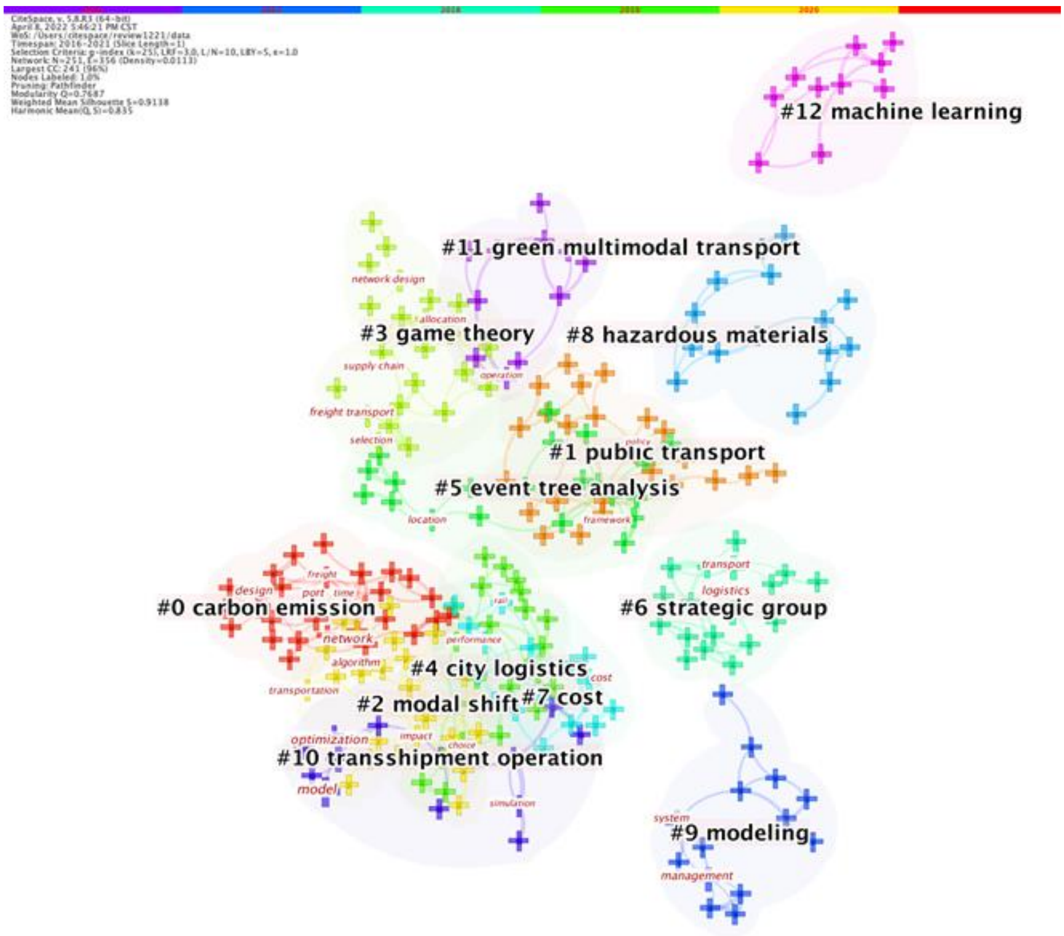

Figure 15. Cluster network map of multimodal freight transport research in recent years (2016-2021)

Table 1. High-frequency countries in the field of multimodal freight transportation research from 1996 to 2021

Country	Frequency	BC	Country	Frequency	BC
Peoples R China	265	0.24	Spain.	47	0.03
USA	197	0.34	France	42	0.12
the Netherlands	115	0.24	England	41	0.17
Italy	86	0.04	Sweden	37	0.15
Germany	66	0.13	Turkey	32	0.01
Belgium	54	0.02	Australia	31	0.09
Poland	53	0.03	Portugal	28	0.02
Canada	47	0.09	-	-	-

Table 2. Top institutions in terms of the number of publications in multimodal freight transportation research from 1996 to 2021

Institution	Country	Frequency	Institution	Country	Frequency
Delft Univ Technol	The Netherlands	72	Univ Maryland	United States	16
Beijing Jiaotong Univ	China	59	Univ Belgrade	Serbia	15
Univ of Hasselt	Belgium	27	Res Fdn Flanders FWO	Belgium	13
Dalian Maritime Univ	China	24	Politecn Bari	Italy	13
Vrije Univ Brussel	Belgium	23	Changan Univ	China	12
Shanghai Maritime Univ	China	21	Eindhoven Univ Technol	The Netherlands	12
Erasmus Univ	The Netherlands	20	Univ Genoa	Italy	12
Southwest Jiaotong Univ	China	19	Wroclam Univ Technol	Poland	12
Natl Univ Singapore	Singapore	17	Vilnius Gediminas Tech Univ	Lithuania	12
Chalmers Univ Technol	Sweden	16	Univ Lisbon	Portugal	11

Table 3. High-frequency authors in multimodal freight transportation research from 1996 to 2021

Author	Country	Frequency	Institution
An Caris	Belgium	24	University of Hasselt
Rudy Negenborn	The Netherlands	24	Delft University of Technology
Cathy Macharis	Belgium	20	Vrije University Brussel
Bart Wiegmans	The Netherlands	14	Delft University of Technology
Gerrit Janssens	Belgium	12	University of Hasselt
Zhu Xiaoning	China	11	Beijing Jiaotong University
Nicola Epicoco	Italy	11	University of L'Aquila

Mariagrazia Dotoli	Italy	10	Polytechnic University of Bari
Teodor Gabriel Crainic	Canada	10	Université du Québec à Montréal
Meng Qiang	Singapore	10	National University of Singapore
Justyna Swieboda	Poland	10	Wroclaw University of Science and Technology
Walter Ukovich	Italy	10	University of Trieste
Sabine Limbourg	Belgium	9	Louvain School of Management
Sun Yan	China	9	Shandong University of Finance and Economics
Mateusz Zajac	Poland	9	Wroclaw University of Science and Technology

Table 4. Ranking of cited authors in the field of multimodal transportation research from 1996 to 2021

Author	Cited counts	Host country	Year
Cathy Macharis	207	Belgium	2004
Teodor Gabriel Crainic	207	Canada	1999
An Caris	164	Belgium	2009
Maryam Steadie Seifi	139	The Netherlands	2014
Yvonne Bontekoning	135	The Netherlands	2004
Milan Janic	105	The Netherlands	2004
Pierre Arnold	97	Belgium	2004
Sabine Limbourg	78	Belgium	2010
Tsung-Sheng Chang	77	Taiwan	2011
Rafay Ishfaq	74	United States	2012
Violeta Roso	73	Sweden	2012
Manish Verma	68	Canada	2008
Emrah Demir	66	The Netherlands	2016
Meng Qiang	64	Singapore	2012
Frank Southworth	62	United States	2000

Table 5. Top 10 keywords in terms of frequency for different periods in the 1996-2021 time span

1996-2005			2006-2015			2016-2021		
Keyword	Frequency	Centrality	Keyword	Frequency	Centrality	Keyword	Frequency	Centrality
model	14	0.55	model	60	0.14	model	123	0.00
terminal	5	0.17	network	38	0.10	network	77	0.00
freight transport	3	0.37	algorithm	35	0.17	optimization	68	0.03
service	3	0.21	freight transport	28	0.15	design	51	0.06
container	3	0.18	system	27	0.10	logistics	50	0.05
policy	3	0.13	optimization	21	0.00	management	50	0.05
algorithm	3	0.07	cost	21	0.26	algorithm	45	0.10
rail	3	0.03	management	20	0.22	cost	42	0.09
flow	3	0.00	logistics	19	0.08	port	38	0.06
integer program	2	0.30	operation	14	0.06	system	37	0.13

Table 6. Top 10 keywords in terms of centrality for different periods in the 1996-2021 time span

1996-2005		2006-2015		2016-2021	
keyword	Centrality	keyword	Centrality	keyword	Centrality
model	0.55	capacity	0.26	framework	0.29
integer program	0.30	cost	0.26	choice model	0.29
service	0.21	choice	0.26	road	0.23

container	0.18	management	0.22	impact	0.21
terminal	0.17	impact	0.21	methodology	0.21
multicommodity	0.15	algorithm	0.17	emission	0.20
policy	0.13	demand	0.16	accessibility	0.20
freight	0.10	freight transport	0.15	assignment	0.19
algorithm	0.07	selection	0.15	time window	0.18
rail	0.03	model	0.14	climate	0.16

Table 7. Top 20 references with strongest citation bursts involved in 2021.

Reference	Strength	Begin	End	Keywords	Topics
Demir E,2016	15.08	2018	2021	Stochastic service network design problem; CO^{2}-equivalent emissions; Travel time uncertainty; Demand uncertainty; Sample average approximation method	Environmental Concerns; Uncertainties and Complexities
Agamez-Arias ADM, 2017	8.00	2019	2021	Systematic Literature Review	Review
Fazayeli S,2018	7.60	2019	2021	Location-routing problem; Time windows; Fuzzy demands; Genetic algorithm	Uncertainties and Complexities; Optimization and Advanced Algorithms
Wang XC,2017	6.79	2019	2021	Economies of scale; Congestion effects; Route choice model; Global optimization algorithm	Behavioral and Competitive Dynamics; Optimization and Advanced Algorithms;
Crainic TG,2018	6.79	2019	2021	Simulation; Taxonomy	Review
Wang R, 2018	6.79	2019	2021	Hub-and-spoke; Fuzzy variable; Memetic algorithm; Local search strategy	Uncertainties and Complexities; Optimization and Advanced Algorithms
Resat HG, 2015	6.71	2018	2021	Synchromodal transportation; Multi-objective optimization; Mixed-integer optimization	Synchromodality
Hrusovsky M, 2018	6.39	2019	2021	CO2-equivalent; Travel time uncertainty; Simulation; Optimization	Environmental Concerns; Uncertainties and Complexities
Baykasoglu A, 2016	5.87	2018	2021	Fleet planning; Fleet sizing and composition; Empty vehicle repositioning; Fuzzy-stochastic programming; Case study	Uncertainties and Complexities; Optimization and Advanced Algorithms
Li L, 2015	5.55	2016	2021	Intermodal freight transport planning; Intermodal container flow control; Receding horizon control	Optimization and Advanced Algorithms
Crainic TG, 2015	5.03	2018	2021	Service network design; Dry port; Logistics; Optimization; Mixed integer programming	Optimization and Advanced Algorithms
Qu Y, 2016	5.03	2018	2021	Service network design; Greenhouse gas emission; Intermodal transfer cost	Environmental Concerns; Modal shift
Sun Y, 2018	4.45	2019	2021	/	Environmental Concerns; Uncertainties and Complexities
Harris I, 2015	4.37	2016	2021	ICT; Barriers to ICT adoption; Technological trends; Cloud computing Internet of Things	Integration of Technology
Assadipour G, 2015	4.04	2019	2021	Rail–truck transportation; Congestion; Hazardous materials; Capacity planning; Non-linear programming; Metaheuristics	Safety and Regulation
Dong CW, 2018	3.98	2019	2021	Modal split; Synchromodality; Supply chain; Review; Stochastic model; Application	Synchromodality; Modal shift
Bouchery Y, 2015	3.76	2018	2021	Hinterland network design; Cost; Carbon emissions; Modal shift	Environmental Concerns; Modal shift
Behdani B, 2016	3.68	2017	2021	Synchromodal freight transport; Transport service scheduling	Synchromodality
Lam JSL, 2016	3.68	2017	2021	Market-oriented approach; Container transport; Port; Carbon emission; Bi-objective optimization	Behavioral and Competitive Dynamics; Environmental Concern
Arencibia AI, 2015	3.45	2019	2021	Freight transport; Discrete choice experiments; Stated preference; Willingness to pay; Discrete choice models	Behavioral and Competitive Dynamics

Note: In order to visualize the information, we have removed the keyword "multimodal transport/intermodal transport". "/" indicates that a keyword was not found.