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Systematic Review

Promoting Sustainability through Synchromodal Transportation: A Systematic Literature Review and Future Fields of Research

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Abstract: Synchromodal transportation is a novel multimodal transportation concept. It builds on a collaboration of shippers and logistic service providers to enable real-time switching between transport modes and mode-free transport bookings, enabling more flexible and sustainable freight transportation. This paper summarizes the current state of research since 2010 by means of a systematic literature review. A comprehensive taxonomy consisting of five dimensions and 13 categories for both qualitative and quantitative papers is developed. The results reveal a mixed picture, with high consistency in geographical areas of synchromodal transportation implementation and suitable modeling of operational disruptions and uncertainties. However, compared to multimodal or road transportation, there is little alignment in the forms of collaboration, network organization, or the advantages of synchromodal transportation. Finally, the main fields for future research are identified, namely business, legal, technological, modeling, and awareness.

Keywords: synchromodal; multimodal; freight; transport; review

Citation: Rentschler, J.; Elbert, R.; Weber, F. Promoting Sustainability through Synchromodal Transportation: A Systematic Literature Review and Future Fields of Research. *Sustainability* **2022**, *14*, 13269. https://doi.org/10.3390/su142013269

Academic Editors: Claudia Caballini, Antonino Canale, Angela Carboni and Fabio Borghetti

Received: 19 August 2022
Accepted: 12 October 2022
Published: 15 October 2022

1. Introduction

The European Union (EU) freight transport industry is responsible for 25.8% of the total GHG emissions, a major factor driving climate change [1]. Existing multimodal freight transport concepts have not been able to counteract the radical ecological changes. The inland freight modal split within the EU, consisting of 77.4% road freight in 2020, shows that neither the goal of a substantial modal shift nor comprehensive decarbonization of the transport sector was advanced in recent years [2].

Promoted by the European Commission, Synchromodal Transportation (SMT) is a new promising freight transport concept. It originated in 2010 in the Netherlands [3]. The revolutionary concept changes the process and organizational forms of existing multimodal freight transport concepts. It can be defined as the "synchronization of physical resources, business processes, and the parallel use of transportation modes in a mode-free way to offer shippers a more flexible and sustainable means of freight transportation." [4]. In this context, synchromodal transport can be seen as a further development of intermodal transport concepts, in which the actors in the transport chain actively work together in a cooperative network in order to plan transport processes flexibly and to be able to switch between transport modes in real-time according to the available resources [5,6].

SMT has the potential to increase the attractiveness of more sustainable transport modalities and thus significantly improve the modal shift. Cost and resource efficiency, as well as reliability and resilience of transports, are guaranteed by unprecedented transparency of freight transport, intensive connectivity of infrastructure, and an in-depth collaboration of all actors involved. However, there is no single universal understanding of SMT. Substantially contrasting emphases are detected in various definitions such as the one by [7]: "Structured, efficient and synchronized combination of two or more transportation modes." or [8]: "A multimodal transportation planning system, wherein the different agents involved in the supply chain work in an integrated and flexible way that enables them to dynamically adapt the transport mode they use based on real-time information from stakeholders, customers, and the logistic network".

As SMT entails profound operational, technical, and business changes, this paper aims to bundle and align existing research approaches. Therefore, a systematic literature review (SLR) is conducted. A conceptual elaboration of SMT is developed, which distinguishes it from previous transportation concepts. Synergies within research on SMT are explored to establish a well-founded and exhaustive overview of the topic. Furthermore, this paper extends the current body of literature. While Acero et al. [8] elaborate on the innovative factors of SMT, they focus on integrating SMT into the supply chain. The SLR presented by Delbart et al. [9] examines intermodal and synchromodal transportation problems but lacks a paper categorization tailored to the innovative features of SMT and their mathematical representation. The SLR conducted by Pfoser et al. [10], which examines antecedents, mechanisms, and effects of SMT, is most similar to this paper. However, their paper focuses solely on the qualitative properties of SMT, disregarding quantitative research, without establishing an individualized taxonomy for qualitative and quantitative papers.

Therefore, there is still a significant research gap in terms of understanding synchromodality holistically, developing a taxonomy to bundle all relevant qualitative and quantitative literature on synchromodal freight transport, comparing the two types of analysis approaches, and identifying future trends. This gap is addressed by answering the research question (RQ):

1. What is the current state-of-the-art of synchromodal transportation?
   To answer this research question conclusively, three sub-questions arise:
   1.1 What is the most relevant literature in the context of synchromodal transportation?
   1.2 How can research on SMT be systematically classified, what trends can be observed, what primary research methods are used, and how do they relate and compare to each other?
   1.3 Which fields for future research can be derived from?

After introducing the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines and the methodology in Section 2, the literature is analyzed by a two-step process [11]. First, descriptive characteristics of the research corpus are summarized in Section 3.1. Thereafter, based on the division of the literature into qualitative, Section 3.2, and quantitative papers, Section 3.3, the development of a taxonomy follows, consisting of distinguishing features on novel SMT characteristics and assessment criteria, which are then clustered into dimensions and categories. The following discussion in Section 4 compares qualitative and quantitative research results, and fields for future research are derived. Finally, we conclude in Section 5.

2. Methodology

Systematic literature reviews aim to better understand a real-life phenomenon and identify and critically evaluate an existing body of knowledge in a precise, rigorous, and replicable method [12]. According to Denyer and Tranfield [12], the four basic principles of an SLR consist of transparency, inclusivity, explanation, and heuristic. Transparency is enabled by three factors: 1. disclosing the processes and methodologies used, 2. presenting the conclusions that are derived, which have clear dependencies on the found evidence in the literature, and 3. by a reflection of the author's values towards the scientific topic to further prevent bias. Furthermore, the articles included in the review play a central but complex role. The quality of the used information sources needs to be appraised to uphold a high standard. The third principle, explanation, covers synthesizing the information into one piece of work, which goes far beyond merely combining the individual articles. Lastly, SLRs present a heuristic consisting of "rules, suggestions, guides, or prototype protocols" [12] instead of fixed solutions to a specific problem. As a result of the four principles that were formerly introduced, five straightforward steps are derived by Denyer and Tranfield [12], guiding this SLR:

First, the research question(s) must be formulated to define the scope of the SLR.

Subsequently, the literature has to be identified in a transparent and documented manner. Based on the research questions, we aim for a holistic view of SMT and have chosen a search string that is as broad as possible. We searched the database Web of Science with the string synchromodal* OR synchro-modal* starting in 2010, the first time synchromodality was mentioned. The broad search led to 83 articles.

To assess the importance of each article, we set up distinct selection criteria:

- The article is written in English;
- Articles have to be peer-reviewed, and if published in a journal, the journal has to be ranked Q2 or higher by the Scimago Journal & Country Rank;
- Non-related papers or papers that only scarcely deal with SMT are excluded. Those papers were identified after reading the title and abstract;
- Conference papers were excluded if they were adopted into journal publications or had no documented methodological approach.

After applying the selection criteria, 56 papers remained. An upstream and downstream search of the citations yielded another six papers. The procedure is summarized in the PRISMA flowchart (Figure 1). Qualitative content analysis sets the framework for analyzing the corpus on synchromodal transportation [13]. Thereby two different techniques can be considered: the deductive and the inductive approach. A deductive approach determines the assessment categories before reviewing each paper. In contrast to the deductive approach, categories are flexibly added during the data evaluation procedure in an inductive approach [14]. Although this procedure yields the need for iterative readings, the inductive approach is chosen due to the novel concept of synchromodal transportation and the lack of knowledge of well-fitting dimensions and categories. Based on the ontological and epistemological idiosyncrasies of SCM and logistics management research and the six idiosyncrasies (theoretical boundaries, unit of analysis, sources of data, study context, definitions and the operationalization of constructs, research methods), as identified by Durach et al. [15], we code and synthesize the literature and develop a taxonomy.

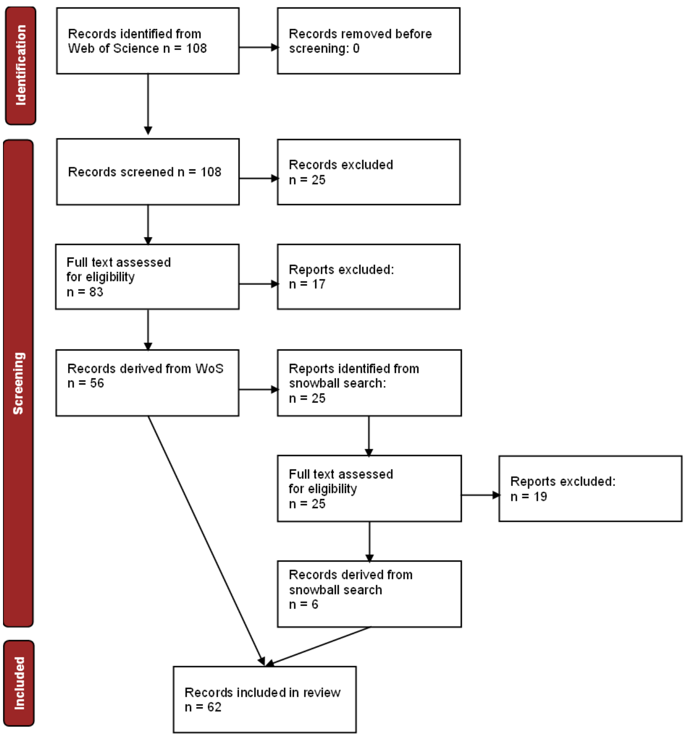

Figure 1. The procedure of SLR jrfm-1905447-tracked to the PRISMA flowchart.

3. Results

To evaluate the corpus of 62 papers, we cluster the content and conduct extensive analysis, resulting in a sequential process. At first, a distinction is drawn between descriptive and content-based analysis. Henceforth, the content-based analysis is performed by distinguishing between qualitative and quantitative papers.

3.1. Descriptive Results

Although already introduced in 2010, the first papers on SMT were published in 2014 (Figure 2). It becomes apparent that the research on SMT started with a qualitative approach, and in subsequent years, papers with a quantitative focus picked up. As synchromodality is a concept coming from the Netherlands, it is no surprise that most research, totaling 35 publications, is located there. The remaining publications are spread worldwide in 15 countries, focusing on Europe.

Figure 2. Publications on synchromodality per year.

As displayed in Figure 3, 20% of the authors were involved in around 50% of the publications on synchromodality. Therefore, although a linear relationship between authors and published papers is not observed, there is no Pareto distribution between authors and published papers. This is a good condition to counter mind bias [16]. Nevertheless, two authors (R. Tadei and B. Atasoy) contributed to more than five papers, and R. R. Negenborn to 16 papers, all focusing on quantitative research. Hence, 28 authors (21%) are engaged in publishing more than one paper. This does not necessarily speak for inconsistency in research, as the research is mainly driven by three universities (Research Group Logistics at Hasselt University, Belgium; Department of Maritime and Transport Technology & Center for Systems and Control both Delft University of Technology, Netherlands; Politecnico di Turino, Italy). We suspect that many Ph.D. students are involved in the research, which increases the number of authors with only one publication on SMT.

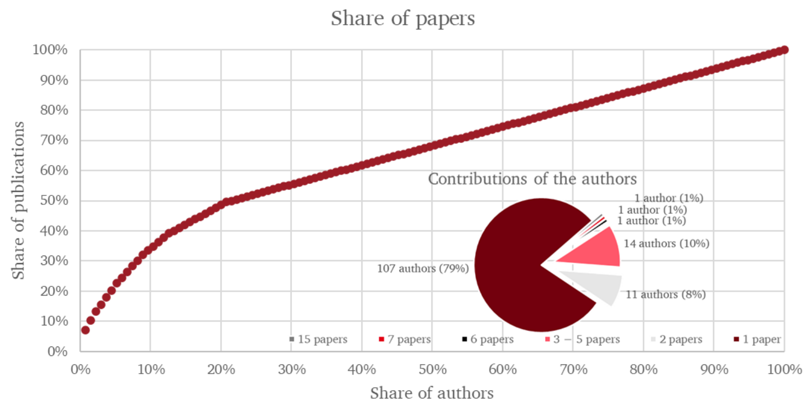

Figure 3. Paper to author and author to paper ratio.

3.2. Results of the Qualitative Papers

In the following, we analyze qualitative papers in a twofold way. Firstly, Six distinguishing features, based on the six idiosyncrasies as identified by Durach et al. [15], are introduced, comparing reoccurring topics within the qualitative literature corpus. After that, the qualitative literature is divided into two dimensions and four categories based on the distinguishing features (Table 1). Hence, a taxonomy of the synchromodal transportation literature is accomplished.

Table 1. Distinguishing features and taxonomy of qualitative papers.

Distinguishing Features	Dimension	Category
• Topic and methodology • Stakeholder focus • Development of synchromodality • SMT application fields • Network organization • Comparative benefits of synchromodality	1. Explanatory research on synchromodality	1. Synchromodality theory refinement 2. Literature reviews on SMT problem modeling
	2. Contextualizing research on synchromodality	3. Case study on SMT implementation 4. SMT implementation linked to further research topics

3.2.1. Distinguishing Features

Six distinguishing features of synchromodality were identified. Each paper's main topic and methodology are broken down into the feature topic and methodology, giving the reader a chance to gain an overview of the paper's findings. As SMT causes disruptive changes in the overall transport organization and execution, the topics of the studied papers are equally broad. The main methodology used is a literature review [7,17], often conducted systematically [7,9]. The second most used methodology is case studies, applied to the analysis of existing SMT implementation projects [18,19], on potential fields of SMT implementation [4,20], or demonstrators and simulation games [21,22].

The second feature, Stakeholder focus, assesses which stakeholders are most emphasized. Although authors agree that SMT impacts all existing stakeholders along the transportation chain [23], some papers highlight certain operators more than others or dedicate their research to one specific stakeholder.

The feature Development of synchromodality analyses aspects in need of expansion, such as technical, operational, or business. Mostly, authors use conceptual approaches to distinguish synchromodality from previous transportation concepts [17,24] and extract their key elements [8,10]. One of the few papers focusing on the business perspective of synchromodality is Perboli et al. [25], which highlights the need for a commercially sustainable solution for all stakeholders involved.

The application of synchromodal theory to case studies, real-world implementations, and research projects is captured by SMT application fields. Due to the conceptual-descriptive or mathematical nature of many papers, and the small number of SMT projects in the real-world, more than 50% of the reviewed papers lack an application of their research to a practical study [10].

How the transport corridors can be organized so that the concept of synchromodality and its benefits are realized, and at the same time, the requirements of all involved stakeholders are taken care of, is considered by the feature Network organization. While analyzing SMT, Tavasszy et al. [17] suppose that SMT is not the sum of a single origin-to-destination transport but rather an integrated way of transportation and therefore needs to be organized from a network perspective. Furthermore, a prerequisite for a functioning SMT network is the intensive exchange and cross-company integration of sensitive data to create a seamless flow of information along the entire transport chain [8,10]. Therefore, collaboration and trust are crucial in vertical relationships and significantly more important in horizontal cooperation [4,18,22].

The last feature, Comparative benefits of synchromodality, summarizes the various envisioned advantages of SMT and clusters these into the four facets planning and execution flexibility, cost- and resource efficiency, sustainability, and transparency.

3.2.2. Taxonomy of Qualitative Papers

A taxonomy comprising two dimensions and five categories is developed to structure the qualitative papers. The first dimension of Explanatory research on synchromodality tends to be more conceptual and introductory and shows a higher illustrative character. This dimension is split into two categories: Synchromodality theory refinement and Literature reviews on synchromodal transportation problem modeling.

With a higher practical reference, the second dimension Contextualizing research on synchromodality, covers papers that frame SMT in a more implementation-oriented way. Three further categories that differ in their focus were disclosed. Case studies on synchromodal transportation implementation comprise companies involved in the logistics context and the resources and tools that are already in place or needed for SMT implementation. Synchromodal transportation linked to further research topics examines the interconnection of the development of synchromodality in literature. Experimental learning about SMT explores the opportunities of serious simulation gaming.

Dimension 1: Explanatory research on synchromodality

Dimension 1 encompasses ten papers, of which six belong to the first category (see Table 2). Both categories include papers that, on the one side, belong to the earliest research on synchromodality [17,24] and, on the other side, to the most recent [8,9]. In general, comparing the papers in dimension one over time, their character becomes increasingly summarizing and unifying as the literature research body they build upon extends as well.

Table 2. Taxonomy of 1. qualitative dimension: Explanatory research on synchromodality.

Dimension	Author	Topic Focus	Methodology *	Stakeholder Focus *	Development of SMT	Application	Network Organization	Comparative Benefits of SMT
1. Dimension: Explanatory research on synchromodality	**Category 1: Synchromodality theory refinement**							
	[8]	Conceptual SMT definition and empirical validation	SLR, I, FG, S	D2D	Conceptual, Verification & Validation	N/A	Using tools from SYNCHRO-NET or IDS company	Flexibility, Efficiency, Sustainability, Transparency
	[10]	Prerequisites and distinguishing factors of SMT	SLR	Shipper, D2D, legal entity	Conceptual	N/A	Neutral network orchestrator	Flexibility, Efficiency, Sustainability, Transparency
	[23]	SMT network organizer and technology to enable SMT	LR	Shipper, TSP, D2D, IM	Conceptual	Rotterdam, CS:SYNCHRONET	5 party logistics provider	Flexibility, Efficiency, Sustainability, Transparency
	[6]	Critical success factors of SMT	LR, CSF, I	Shipper, TSP, D2D, IM, legal entity	Conceptual, Verification & Validation	N/A	Not explicitly mentioned	Flexibility, Efficiency, Sustainability, Transparency
	[17]	Enablers/barriers of SMT	LR	Shipper, TSP, D2D, IM, legal entity	Conceptual	N/A	Existing actors along the transportation chain or ICT platform	Flexibility, Efficiency
	[24]	Ontology to create definitions of transportation concepts	LR	N/A	Conceptual	N/A	N/A	Flexibility, Efficiency
	Category 2: Literature reviews on synchromodal transportation problem modeling							
	[9]	SMT problems dealing with uncertainty	SLR	TSP, D2D, IM	Mathematical	N/A	N/A	N/A
	[26]	SMT problem classification	LR	N/A	Mathematical	N/A	Global controller	Flexibility, Efficiency, Sustainability
	[27]	Methods for SMT planning in inland container networks	LR, CS	Shipper, TSP, D2D, IM	Mathematical, Conceptual	European Gateway Services, Rotterdam	Network operator	Flexibility, Efficiency, Sustainability
	[5]	Problem modeling and solution techniques	LR	Shipper, TSP, D2D, IM	Mathematical	N/A	N/A	Flexibility, Efficiency

* **Methodology**: LR = Literature review | I = Interview with experts | FG = Focus groups with transport logistics experts | S = Survey amongst transport logistics experts | CS = Case study | * **Stakeholder focus**: D2D = Door-to-door service provider | TSP = Transportation service provider | IM = Inframanager.

The category Synchromodality theory refinement extracts the innovative features and their distinction from existing transportation concepts while also elaborating on characteristics, critical success factors (CSFs), or barriers [8,10].

Although literature reviews on mathematical SMT problems in the second category exhibit the analysis of quantitative papers, they are summarizing and qualitative in their nature. In addition to these methodologies, surveys and interviews can be conducted to collect data [28]. Each of the four examined reviews focuses on different areas of mathematical transportation planning problems and covers different periods in their analysis. Analyzing mathematical SMT problems, distinguishing them from existing multimodal transport problems, and striving to set up a framework for different group characteristics of SMT modeling problems are core topics of the latter category.

Dimension 2: Contextualizing research on SMT

Dimension 2 comprises 13 papers, of which *Case studies on synchromodal transportation* implementation represent the most prominent category with seven papers, followed by *Synchromodal transportation linked to further research topics and Experimental learning about synchromodal transportation* (see Table 3).

Moving from theory to practice, the papers in category 3 elaborate on the possibility of implementing synchromodality and assess its degree of implementation and the necessary prerequisites. Tsertou et al. [20] and Bol Raap et al. [29] are similar in that they present the development of a technological tool to introduce synchromodality. The second set of papers examines how a-modal booking of shippers can be realized [30] and how to establish synchromodality as a whole in a country [4]. The remaining papers cover case studies on how far SMT implementation has advanced.

The papers in category 4 connect synchromodality with two further research directions: slow steaming and physical internet (PI). Fostering sufficient technological and managerial conditions to establish the former and accounting for the success of the latter is assumed by the implementation of SMT. A different yet promising approach to transferring the theoretical concept of synchromodality to newcomers in a tangible way is serious simulation gaming. Used by Buiel et al. [21] and Kurapati et al. [22], they strive to reveal the benefits of comprehensive planning freedom to Dutch logistics and transport experts through simulation games.

Table 3. Taxonomy of 2. qualitative dimension: Contextualizing research on synchromodality.

2. Dimension: Contextualizing research on synchromodality	Author	Topic Focus	Method-ology *	Stakeholder Focus	Development of SMT	Application	Network Organization	Comparative Benefits of SMT
	Category 3: A case study on synchromodal transportation implementation							
	[30]	Control over transport mode	S	Shipper, TSP, D2D	Operational, Business	N/A	LSP as orchestrator	Efficiency, Flexibility
	[18]	Degree of SMT within companies	Q, I, CS	Shipper, TSP, D2D, IM	Operational, Verification & Validation	Continental & intercontinental companies	Logistics orchestrator via control tower	Flexibility, Efficiency
	[19]	Degree of SMT at European ports	LR, FG, CS	TSP, D2D, IM	Conceptual, Operational, Technical	Rotterdam, Antwerp, Hamburg	Central institution including a central platform	Flexibility, Efficiency, Sustainability
	[4]	SMT implementation in Ghana	LR, CSF, RA, Q SWOT	Shipper, TSP, D2D, legal entity, IM	Conceptual, Operational	CS: Ghana	LSP as orchestrator + common platform as a control tower	Flexibility, Efficiency, Sustainability, Transparency
	[29]	Automated retrieval of real-time data	I, FG	Shipper, TSP, D2D	Operational, Technical	CS: 4PL at the Schiphol Airport	4PL using a common data platform	Flexibility, Efficiency, Transparency
	[20]	Container consolidation	LR, CS	Shipper, TSP, D2D	Technical	CS: Piraeus, Greece	Cloud-based cooperation portal	Flexibility, Efficiency, Transparency
	[31]	Architecture for real time data	CS	Shipper, TSP	Operational, Technical	N/A	Control tower	N/A
	Category 4: Synchromodal transportation linked to further research topics							
	[32]	Introduction of smart steaming	LR, SWOT	TSP, D2D, IM, legal entity	Operational, Technical	N/A	LSP as orchestrator + common information platform	Flexibility, Efficiency, Sustainability
	[7]	Correlation of SMT and PI	SLR	TSP, D2D	Operational, Technical	N/A	Multi-stakeholder platform	Flexibility, Efficiency, Sustainability
	[33]	SYNCHRO-NET project	LR, CS: gaming	Shipper, TSP, D2D, IM	Operational, Technical, Business	SYNCHRO-NET	SYNCHRO-modal supply chain eco-NET	Flexibility. Efficiency, Sustainability, Transparency
	[25]	Business models in the field of slow steaming	LR, S, BMC, VPC	Shipper, TSP, D2D, IM	Operational, Technical Business	SYNCHRO-NET	One single platform	Flexibility, Efficiency, Sustainability, Transparency
	[22]	Test information strategies	S, FG, CS: gaming	IM, legal entity	Operational	Gaming CS: Modal manager	IM as SMT network orchestrator	Flexibility, Efficiency, Sustainability, Transparency
	[21]	Teach SMT concept	Q, CS: gaming	Shipper, TSP, D2D	Operational	Gaming CS: Synchro-mania	Forwarder as a network orchestrator	Flexibility, Efficiency, Sustainability

* **Methodology**: Q = Structured questionnaire | SWOT = Strengths, weaknesses, opportunities, threats analysis | RA = Regression analysis | BMV = Business Model Canvas | VPC = Value Proposition Canvas.

3.3. Results of the Quantitative Papers

Similar to the qualitative analysis, an initial explanation and overview of the applied evaluation criteria are provided. Instead of distinguishing factors that examined whether and how certain areas of synchromodality are covered in the qualitative papers, 13 assessment criteria are applied to the quantitative papers. The reason for this slightly different approach is that the analyzed quantitative papers are mostly very distinct about certain factors and thus can be clearly assessed. Based on the detailed assessment criteria, a taxonomy comprising three dimensions and nine categories is accomplished (Table 4).

Table 4. Assessment criteria and taxonomy of quantitative papers.

Assessment Criteria	Dimension	Category
General criteria • Overarching problem • Mathematical model • Solution method • Planning horizon • Optimization objective • Information evolution and quality **Synchromodal transportation-specific criteria** • System characteristics • Scope of horizontal collaboration • Transport service characteristics ○ A-modal booking of shippers ○ En-route mode and tour recalculation ○ Predefined truck routes ○ Predefined departure/arrival schedule	1. Shipment matching problems in synchromodal transportation	1. Deterministic problems 2. Online and stochastic problems 3. Synchromodality and intermodality comparison
	2. Synchromodal network mapping	4. Synchromodal transshipment location planning 5. Synchromodal transportation revenue management 6. Transport mode schedule and tour determination 7. Decentralized decision-making
	3. Synchromodal transportation application	8. Digital planning tools for synchromodal transportation 9. Synchromodal transportation in the supply chain context

3.3.1. Assessment Criteria

Although the SMT problems are based on classic transportation problems [34], their complexity far exceeds the usual problem. This is primarily due to the a-modal booking of shippers and real-time switching until shortly before, but also during, transport execution. In two-thirds of cases, the underlying mathematical formulations are recognized as mixed integer (MIP) or integer problems (IP). Furthermore, simulation and Markov Chains are applied. Most papers deal with operational issues, thereby integrating real-time information evolution and stochastic information.

Nearly 80% of the papers apply their models to intra-continental transportation. Moreover, 29 papers refer to port hinterland transportation in their studies. The Port of Rotterdam as the source or sink for an SMT network appears especially suitable, as it opens the door for the tri-modal Rhine corridor. Besides, also the hinterland corridors from the Greece port in Piraeus to Prague [35], the Shanghai container hinterland [36], and the Klaipeda seaport hinterland in Lithuania [37] are subject of SMT network analysis.

The majority of 25 papers test their proposed model in a case study. However, the case studies differ significantly in size. As presented by [34] or [35], smaller networks more often relate to synthetic data and comprise less than ten terminals. In general, case studies on SMT with small scope must be viewed with caution since important features such as en-route real-time switching, integrated network planning, and infrastructure interconnection only develop their potential with increasing network size. On the contrary, more extensive networks cover hundreds of shipment requests, links and nodes, hundreds of services, and several dozen terminals [38,39].

Adapted from Juncker et al. [26], the System characteristics distinguish between four model cases that differ in the SMT actors' knowledge level and the optimization perspective. In limited models, information availability and optimization are local, unlike cooperative models, where information is still only available locally, but optimization is global. A model is called selfish if, on the one hand, global information is available for each stakeholder, but on the other hand, optimization is still local. Lastly, social models assume global information and optimization. In addition, an extension of the classification is provided by further separating social models by their organizing scope.

Although global optimization requires the highest level of mutual trust among transport operators, it was chosen by more than 69% of all papers (see Figure 4). Nineteen papers based their assumptions on a social orchestrator that, when equipped with global information, optimally organize an entire synchromodal network, testifying to the authors' great interest in optimization approaches for entire transportation networks. Nonetheless, representing the second largest identified group, papers identified with selfish system characteristics reveal a wide range of coordination forms within synchromodal networks.

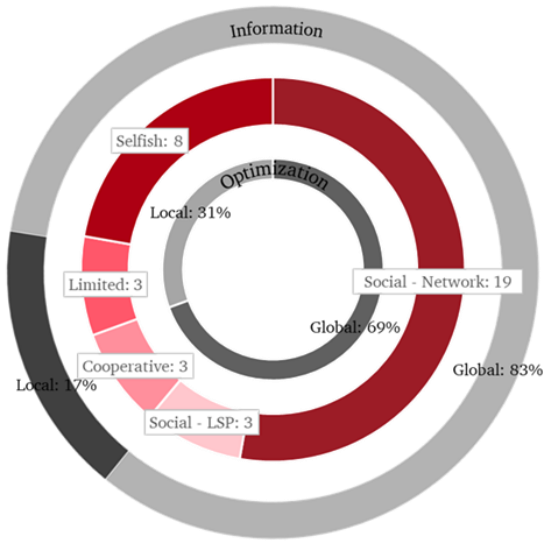

Figure 4. System characteristics analysis results.

The evaluation of the Cooperation mechanisms shows that, with almost 70% of all papers, a full horizontal collaboration between the transport actors is modeled most frequently.

The Transport service characteristics differ substantially from those of previous multimodal transport concepts. Four underlying criteria were determined to assess how the authors understand real-time switching and integrated network planning as a crucial part of synchromodality and to what extent these are integrated into the model formulations. As a prerequisite to other service criteria, the models were reviewed for a-modal booking of the shippers. Whereas this is a prerequisite for real-time switching before transport execution, it was also examined if the model promoted en-route mode or tour re-scheduling for the shipped cargo in case of unforeseen disturbances or new transport orders. Closely related, truck tours were analyzed concerning whether or not they are predefined or flexible.

3.3.2. Taxonomy of Quantitative Papers

Based on three dimensions and ten subcategories, papers with similar content are compared and clustered. Dimension 1, Shipment matching problems in SMT, covers operational decision processes under varying scenario conditions. Dimension 2 addresses the Transport network mapping under the influence of synchromodality features. This comprises strategic terminal planning, transport service pricing, transport mode schedule planning, and decentralized cooperation mechanisms. Lastly, dimension 3 focuses on Adapting synchromodality in a supply chain context and developing digital tools for SMT applications.

Dimension 1: Shipment matching problems in SMT

The first and largest dimension comprises 16 papers concentrated on synchromodal shipment matching. These are clustered according to their information quality, and their results are compared to intermodal solutions in category 3 (Table 5).

Deterministic shipment matching problems focus mainly on transport mode and route real-time switching, implying integrated network planning and a centralized network organization. Whereas [40] highlights a-modal booking, Nabais et al. [41] and Guo et al. [42] concentrate on real-time switching as the central aspect of synchromodality.

The second category consists of Online and stochastic problems. Like Guo et al. [36], all three papers by Guo et al. [34,40,42] consider a digital matching platform, yet with different dynamic and stochastic variables. In contrast, the models presented by Rivera and Mes [43–45] are not placed in an application-based context but rather stand for themselves. While [43] and [44] seek overall transportation cost minimization, profit maximization is the objective of [45].

The third category includes three papers that specialize in Comparing synchromodal and intermodal transportation, i.e., in the Rotterdam transport hinterland. Whereas in SMT, a-modal booking allows for flexible re-scheduling in case of delays, shipments in intermodal transportation remain with their initial transport plan. This fact is considered a distinct advantage in the current literature on SMT, but the findings of [39,46,47] do not provide unconditional evidence for this.

Table 5. Taxonomy of 1. quantitative dimension: Shipment matching problems in synchromodal transportation.

1. Dimension: Shipment matching problems in synchromodal transportation

Author	Overarching Problem*	Mathematical Model *	Solution Method *	Planning Horizon	Optimization Objective *	Information Evolution	Information Quality	System Characteristics	Scope of Horizontal Collaboration	A-Modal Booking	En-route re-Scheduling	Truck Tours	Departure/Arriv Schedule
Category 1: Deterministic problems													
[42]	DSM	MIP, BIP	A: HA	O	Ec: C, E, Delay	Online. SR	Deterministic	Social: network	DTM, STM, TTM	✔	X	Fixed	Road: flexible
[48]	Network design	MOMIP	E: Solver	O	Ec: C; En: CO_2; P: TT	Online: D, TT, truck speed	Deterministic	Social: network	DTM, STM, TTM	✔	✔	Flex	Road: flexible
[40]	Perishables goods	IP	E: Solver	O	En: quality loss	Offline	Deterministic	Social: network	DTM; STM	✔	X	Fixed	All: Fixed
[41]	Cargo allocation	State-space model	A: HA	O	Ec: C; En: E	Online: D	Deterministic	Cooperative	TTM	✔	X	Fixed	Road: flexible
Category 2: Online and stochastic problems													
[49]	DSGSM	MIP	A: RLA	O	Ec:P	Online: TT	S: TT	Social: network	DTM, STM, TTM	✔	✔	Fixed	Road: flexible
[45]	Container scheduling	MDP	A: ADP-VPI	O	Ec: P	Online: D, Resource capacity,	S: D	Social: LSP	Full: DTM, TTM	✔	✔	Fixed	Road: flexible
[38]	DSGSM	MIP	A: HSA	O	Ec: P	Online: SR, TT	S: SR, TT	Social: network	DTM, STM, TTM	✔	✔	Fixed	All: Flexible
[50]	DSSM	MIP, BIP	A: SAA, PHA	O	Ec: C, E, Delay	Online: SR	S: SR	Social: network	DTM, STM, TTM	✔	✔	Fixed	Road: flexible
[37]	SITM	IP	E: Solver	O	P: TT,	Online: TT	S: TT	Social: network	STM	✔	X	-	All: Flexible
[44]	STSSN	MIP, MDP	A: MH, ADP	O	Ec: C	Online: D	S: D	Social: network	DTM, STM, TTM	✔	X	Flex	All: Flexible
[51]	DSSM	IP	A: Solver	O	Ec: C	Online: D	S: D	Social: network	-	✔	X	Fixed	Road: flexible
[43]	Service selection	MDP	A: ADP	O	Ec: C	Online: D, TT	S: D	Social: network	DTM, STM, TTM	✔	✔	Fixed	Road: flexible
[36]	DSSM	Two-stage	A: GA	O	Ec: P	Online: D	S: D	Social: network	DTM	✔	X	Flex	All: Fixed
Category 3: Synchromodality and intermodality comparison													
[47]	SMT planning	MDP	E: Back-tracking	O	Ec: C	Online: TT, resource capacity	S: TT, capacities	Selfish	DTM, STM, TTM	X	✔	Fixed	Road: flexible
[46]	Long-distance digital twin	Simulation	A: Simulation optimization	O	Ec: C, TT; En: E P: reliability,	Online: order costs, lead-time	S: order costs, lead-times, TT	Selfish	Limited: DTM, STM	X	✔	Flex	Road: flexible
[39]	RS-BCR	MIP	E: CS-BFAA	O	Ec: C	Online: D	S: D	Social: network	DTM, STM, TTM	✔	X	Flex	Road: flexible

* **Overarching problem**: DSM = Dynamic and stochastic matching | DSSM = Dynamic and stochastic matching | DSGSM = Dynamic and stochastic global shipment matching | SITM = Synchronized intermodal traffic management | STSSN = Service and transfer selection problem in a synchromodal network | RS-BCR = Repeated schedule-based cheapest route | * **Mathematical model**: BIP = Binary integer programming | MOMIP = Multi-objective mixed-integer programming | * **Solution method**: E = Exact | A = Approximate | HA = Heuristic algorithm | RLA = Reinforcement learning approach | ADP-VPI = Approximate dynamic programming-Value of Perfect Information | SAA = Sample average approximation | PHA = Progressive Hedging Algorithm | GA = Genetic algorithm | CS-BFAA = Capacitated schedule-based flow assignment algorithm | * **Optimization Objective:** Ec = Economic | En = Environmental | P = Performance | C = Cost | TT = Travel Time | P = Profit | E = Emission | * **Information evolution and quality:** D = Demand | SR = Spot Request | S = Stochastic.

Dimension 2: Synchromodal network mapping

Fifteen papers in four categories deal with the framework of a synchromodal network, differentiating between strategic, tactic, and operational levels as well as decentralized cooperation mechanisms (Table 6). On a strategic level, this includes the consideration of SMT characteristics in the positioning of transshipment terminals. At the tactical level, the papers in category 5 describe how transportation pricing policies need to be adjusted to support SMT. Category 6 is characterized by the effort to determine the schedules and route and tour planning of the vehicles within a synchromodal network. In contrast to an often-assumed centralized network organization, several decentralized cooperation mechanisms are introduced by the papers in category 7.

Category 4 includes two papers addressing the strategic issue of how transhipment locations can be optimally placed in an SMT network. Next to the already immensely complex challenge of ideally locating facilities within a transport network, Crainic et al. [52] also consider the operational processes of a multi-period Synchronized Location-Transshipment Problem already at the strategic planning horizon.

Two papers cover the Tactical planning problem of defining the transportation product conditions. In general, products in the transportation context are defined by their price, lead time, and resulting service level. In contrast to traditional pricing mechanisms, van Riessen et al. [53] and van Riessen et al. [54] designed new pricing strategies that consider the synchromodal characteristics of a-modal booking and real-time switching.

Truck or barge routing, as well as schedule determination, is the focus of category 6. Operational transport means and container movements are represented by various cargo allocations and VRPs [55–57]. Moving from tour optimization to transport network resource scheduling, Behdani et al. [58] focus on rail and barge schedules.

Cooperation mechanisms that are significantly different from previously mentioned cooperation mechanisms are considered in the category of Decentralized decision-making. Instead of a central unit controlling the entire network, the coordination of routes and schedules is based on a decentrally organized process. Instead of assuming complete horizontal cooperation among actors within a synchromodal network, Larsen et al. [59] and Li et al. [60] present various coordination strategies to achieve intensified cooperation among transport operators, and Juncker et al. [61] model an agent-centric synchromodal network.

Table 6. Taxonomy of 2. quantitative dimension: Synchromodal network mapping.

Dimension: Synchromodal network mapping

Author	Overarching Problem *	Mathematical Model	Solution Method *	Planning Horizon	Optimization Objective	Information Evolution *	Information Quality	System Characteristics	Scope of Horizontal Collaboration	A-Modal Booking	En-route re-Scheduling	Truck Tours	Departure/Arriva Schedule
Category 4: Synchromodal transshipment location planning													
[52]	SLTP	MIP	E: Solver	S	Ec: C	Offline	Deterministic	Social: LSP	TTM	N/A	N/A	N/A	N/A
[62]	TLAP	Two stage	A: PHA	S-T	P: max. transportation utility	Offline	S: transship-ment capacities	Social: network	TTM	N/A	N/A	N/A	N/A
Category 5: Synchromodal transportation revenue management													
[54]	Cargo fare class mix	Markov Chain	A: Greedy	T	Ec: P	Offline	S: D	Social: network	Limited: DTM, STM	✔	X	Fixed	Fixed
[53]	Cargo fare class mix	MIP	E: Solver	T	Ec: revenue	Offline	S: D	Selfish	None	✔	X	Fixed	Fixed
Category 6: Transport mode schedule und tour determination													
[63]	DSSM & Resource schedul	Two stage & IP	A: SAA	O	Ec: C	Online: D, capacity	S: D, capacity	Limited	Limited: DTM, STM	✔	X	Fixed	Flexible
[55]	Cargo allocation and vehicle routing	State-space commodity flow	E: Solver	O	Ec: C	Online: TT, resource capacity	S: TT	Social: network	DTM, STM, TTM	✔	✔	Flex	Road: flexible
[56]	PDPT	MIP	A: ALNS	O	Ec: C; En: CO_2	Online: TT	S: D	Social: network	DTM, STM, TTM	✔	✔	Flex	Flexible
[57]	Online order assignment	IP	E: Solver	O	Ec: C	Online: D, AA	S: D, AA	Selfish	DTM, STM	✔	✔	Flex	Flexible
[64]	Network design	IP	E: Solver	O-T	Ec: C	Offline	Deterministic	Selfish	None	✔	X	Flex	Road: flexible
[65]	SMT replanning	MIP	E: Solver	O	Ec: C	Online: D, TT shipment release time	Deterministic	Social: network	DTM, STM, TTM	✔	✔	Fixed	Flexible
[58]	Network resource schedule	IP	E: Solver	O	Ec: C	Offline	Deterministic	Social: LSP	DTM	✔	X	Fixed	Flexible
Category 7: Decentralized decision-making													
[59]	Resource schedule	MIP	E: Solver	O	Ec: C	Online: D, cost	Deterministic	Limited	Limited: DTM, STM	✔	X	Fixed	Flexible
[66]	Inland vessel coordination	CP, MIP	E: Solver A: LNS	O	P: Efficiency	Offline	Deterministic	All	Limited to full: STM, TTM	N/A	X	-	Flexible
[61]	Dynamic traffic assignment	Simulation	A: Greedy	O	Ec: C	Online: TT	S: TT	Limited, selfish	DTM, STM, TTM	X	✔/X	Flex	Road: flexible
[60]	Cooperative model predictive container flow control	Simulation	A: ALR, ADMM	O-T	Ec: C	Online: D, resource capacity	Deterministic	Cooperative	Limited: DTM, STM, TTM	✔	X	-	Road: flexible

* **Overarching problem**: SLTP = Single-commodity multi-period synchronized Location Transshipment Problem | TLA = Stochastic multi-period Transshipment Location-Allocation Problem | CP = Constraint Programming | * **Solution method**: (A)LNS = (Adaptive) Large Neighborhood Search | ALR = Augmented Lagrange Relaxation | ADMM = Alternating Direction Method of Multipliers | * **Information evolution:** AA = Appointment approval.

Dimension 3: SMT application

Papers in the third dimension are characterized by their high application relevance (Table 7). Category 8 represents digital planning tools. Category 9 broadens the focus beyond a purely transportation-based synchromodality view to a synchromodal supply chain.

Del Vecchyo et al. [67] and Dobrkovic et al. [68] research prerequisites to enable digital tools for SMT. The former observes that in operational SMT planning, costs and transport times are the most important KPIs. Dobrkovic et al. [68] focus on IT platforms in the context of SMT that require reliable ship arrival and delay data. This information is a prerequisite for barge planning of LSPs, which are given the freedom by synchromodality to replan hinterland transports flexibly. The overall goal of papers concerning digital planning tools for synchromodal transportation is to provide a planner of SMT with a support tool. Focusing on the transport route from Piraeus to Prague, Kapetanis et al. [35] introduces a support tool for LSPs, which enables transparent tour planning. Offering various multimodal alternatives, the tool entirely relies on a-modal booking, the horizontal collaboration of transport operators, and integrated network planning.

The last category is characterized by the combination of SMT and supply chain optimization. Economic, environmental, and performance-oriented synchromodal decisions are considered part of a corporate supply chain. Hence, material and information synchronization is not limited to SMT processes but applies to the entire supply chain. Synchromodality no longer only represents a transportation concept but rather a supply chain principle. [69] shape the term Synchromodality from a Supply Chain Perspective (SSCP) and model the optimal freight allocation within an SMT network while simultaneously considering inventory costs. The authors argue that although synchromodal rail-road transportation causes higher travel times than road-only transportation, SSCP reduces the total logistics costs by 6% through the cost advantage of SMT. However, the limited transport corridor of the presented case study neglects flexible replanning during the transport execution. On the contrary, [70] includes real-time switching of transport modes into their synchromodality decision rule.

Table 7. Taxonomy of 3. quantitative dimension: Synchromodal transportation application.

3. Dimension: Synchromodal transportation application

Author	Overarching Problem *	Mathematical Model	Solution Method	Planning Horizon	Optimization Objective	Information Evolution	Information Quality	System Characteristics	Scope of Horizontal Collaboration	A-Modal Booking	En-route re-Scheduling	Truck Tours	Departure/Arriva Schedule
Category 8: Digital planning tools for synchromodal transportation													
[67]	MCMCF	MIP	E: Solver	O	P: flexibility, robustness, customer satisfaction	Offline	S: TT, handling times	N/A	Full: DTM, STM, TTM	✔	✔	Flexible	Road: flexible
[68]	Maritime pattern extraction	Simulation	A: GA	O	Ec: C, TT; En: E	Online: vessel position data	S: Ship waypoints	Cooperative	N/A	N/A	N/A	N/A	N/A
[71]	SMT cargo allocation	MIP	E: Solver	O	Ec: C, TT	Offline	Deterministic	Social: network	None	✔	X	Flexible	Fixed
[35]	Exceptional Handling & Real-time switching	N/A*	N/A*	O	Ec: C, TT, fuel consumption	Online: TT, C	Deterministic	Selfish	N/A	X	✔	N/A	N/A
[72]	Multi-objective k-shortest path	Simulation	A: Sequential heuristic	O	Ec: C; En: CO_2;P: reliability	Online: SR	S: TT	Social: network	Full: DTM, STM, TTM	✔	✔	Fixed	Road: flexible
Category 9: Synchromodal transportation with Supply Chain focus													
[70]	Multimodal dual sourcing	MIP	E: Solver	O	Ec: C	Online: D, lead-times	S: D, lead-times	Selfish	Full: DTM, STM, TTM	X	✔	Fixed	Fixed
[69]	Dynamic inventory replenishment	IP	E: simulation-optimization	O	Ec: C	Online: D	S: D	Selfish	None	X	X	Fixed	Road: flexible
[73]	SMT network design	MIP	E: Solver	S	En: E, C, energy consumption	Offline	Deterministic	Limited	N/A	X	X	N/A	N/A

* **Overarching problem**: MCMCF = Minimum Cost Multi-Commodity Flow problem.

4. Discussion and Fields of Future Research

This paper compared qualitative and quantitative papers, providing insights into commonalities and differences in SMT characteristics. While the assumptions and results of the papers have been analyzed and compared in detail so far, this discussion offers a comparison on a meta-level and identifies open research fields in the context of SMT. As identified in the descriptive analysis, research on SMT started with qualitative approaches, and it was only afterward that quantitative papers were published. Therefore, the extent to which the quantitative papers' models reflect the theoretical findings of the qualitative papers on SMT is examined, and, further, it is analyzed to what degree the quantitative papers' modeling results support the qualitative papers' conclusions regarding the positive effects of SMT.

An analysis of the planning horizons of the quantitative models has shown that SMT problems can indeed be divided into the conventional categories of operational, tactical, and strategic, as assumed by Delbart et al. [9]. However, planning horizons increasingly merge in SMT. Due to the real-time synchronization and a global network orchestrator, the analysis of the quantitative papers dealing with strategic hub-location problems revealed that the operational level needs to be taken into account even more than in previous multimodal transportation problems. An operational-tactical hybrid of planning problems in SMT arises. Contrary to fixed transport resources with fixed schedules, the short-term operational demand determines which means of transport are used and when [65].

The quantitative papers provide a realistic representation of operational uncertainties in SMT, as identified by qualitative papers. More than 50% of the papers model the SMT problems using stochastic and dynamic parameters. In addition, the geographical references of the case studies in the quantitative papers are well aligned with actual SMT application areas. Nearly 75% of the models refer to port hinterland transportation. Moreover, the claim of [27] that existing models describing multimodal transportation problems are unsuitable for representing SMT, is confirmed. Due to real-time switching and horizontal collaboration within SMT, quantitative papers are developing new models precisely tailored to these characteristics [72].

At the same time, many inconsistencies exist between the results of the qualitative papers and the representation of SMT in the quantitative models. For example, the form of cooperation between the actors and the acceptance of a central network organizer. Several qualitative papers conclude that horizontal cooperation, a-modal booking, real-time switching, and the preceding mind-shift to transfer competencies and responsibilities represent the greatest challenges for the introduction of SMT [17]. Since today's market positions are based on a business model of data evaluation, logistics companies tend to avoid these characteristics of SMT [18]. Furthermore, qualitative papers emphasize that legal barriers must first be overcome before such sensitive data can be exchanged. On the other hand, more than 70% of the quantitative papers build their models on full horizontal cooperation. Another issue concerns the optimization objectives of the quantitative papers. While SMT is to be introduced especially because of its environmental friendliness and promised outstanding potential for sustainable cargo transportation, 70% of all quantitative papers optimize economic objectives exclusively.

While qualitative conceptual-oriented papers exclusively expect cost benefits from the application of SMT [4,8], it turns out that handling costs and pro-active route and mode switching lead to higher costs compared to static intermodal transport [7]. Furthermore, the conclusion of the qualitative papers that SMT leads to a reduction in road freight transport has to be considered in a differentiated way. However, the quantitative papers agree that SMT increases the share of rail transportation, [39] documenting a drastic increase in road transport in the vicinity of transshipment terminals.

Synchronizing the papers' results and comparison to current drivers impacting the European transport sector opens the door for future research fields on SMT. Five distinct research areas are disclosed and summarized in Table 8.

Table 8. Fields of future research on synchromodality.

Field of Development	Open Research Fields
Business	▪ Differentiated investigation of the effects of SMT on the cost development of individual cost units and transport actors in comparison to currently used multimodal concepts. ▪ Conceptual design and modelling of a centralized entity with a focus on profit and loss sharing mechanisms as well as more realistic SMT pricing strategies, considering spot requests, demand variations, and cannibalization effects between fare classes. ▪ Further investigation on determining the tasks of a platform organizing SMT and whether an existing actor or an additional player will manage it. ▪ Determination of which overall goals a platform for organizing an SMT network pursues.
Legal	▪ Determination of which legal barriers impede the requested horizontal collaboration and how these can be overcome. ▪ Clarification of liability, data security, and insurance issues of a-modal booking and real-time switching.
Technological/Physical	▪ Investigation on how the connectivity of loading units can be established through IoT technology. ▪ Impact of infrastructure interoperability issues on anticipated en-route real-time switching. ▪ Investigation of which loading units are best suited to be used in SMT.
Mathematical Modeling	▪ Consideration of larger SMT networks in numerical experiments, consisting of multiple transshipment points and transport corridors offering several transport modality alternatives. ▪ Elaboration of a model incorporating transport modalities using alternative fuels or engines (e.g., electric trucks, Methanol-powered barges). ▪ Consideration of truck driver shortages. ▪ Modelling based on data from SMT real-life applications. ▪ Analysis and quantification of cost and travel time effects of SMT shipments facing short-duration disruptions.
Awareness and implementation	▪ Expansion of existing serious gaming methods and expansion of their application among employees are directly affected by process changes induced by SMT. ▪ Further investigation and verification of existing results regarding conditions and compensations under which shippers agree to a-modal booking. ▪ Further investigation and verification of existing results regarding the implementation challenges of individual SMT characteristics differentiated by cultural and legal conditions.

Considering *future research on business aspects of* synchromodality, business models, a two-sided platform, and trust are the key subjects. While various quantitative papers represent an orchestrator and its tasks, necessary business models, including profit and loss sharing mechanisms for all engaged actors within a centralized network organization, are entirely missing. The necessity to establish profit and loss compensation mechanisms that treat all involved parties fairly and are accepted by all involved stakeholders becomes even more critical when realizing that SMT causes very different cost changes.

Several papers [4,33] highlight *legal barriers*, liability, and insurance issues to the proposed horizontal collaboration. However, no paper deals with the legal controversy of what laws at national and European levels are involved and which specific changes are required to allow for intensive data sharing, real-time switching, and horizontal collaboration in SMT.

Although identified as one of the requirements for SMT by qualitative research and presumed in quantitative papers, *loading units and interconnections of infrastructure* remain an uncovered prerequisite of SMT in scientific literature. No paper deals with physical interoperability problems of SMT that exist between neighboring countries and impede real-time switching. Furthermore, the characteristics of loading units are not mentioned, or containers are assumed to be most suitable for real-time switching. While the technologies of Blockchain and IoT are emerging, their application to data security in horizontal collaboration and connectivity of loading units, respectively, have yet to be explored.

The remarkable share of quantitative papers in the overall literature corpus could not lead to the clarification of all *modeling issues concerning* SMT but rather represents the beginning of the transport problems to be investigated. In general, all mathematical models should include data from real-life SMT projects. To better reflect ongoing trends affecting the European transportation industry, truck driver shortages, alternative fuels and engines (e.g., electric trucks, Methanol powered barges), as well as short-duration disruptions, need to be considered in modeling SMT problems.

As the concept of synchromodality still occupies a niche position in the discussion on sustainable transport logistics, *awareness* needs to be strengthened. Studies on increasing shippers' willingness regarding a-modal booking [30] and the methods of serious gaming [18,19] can help foster this development. The combination of qualitative, which form the basis for modeling assumptions, and quantitative literature is an essential approach to cover the presented areas of future scientific research on synchromodality.

5. Conclusions

The purpose of this paper is to provide a systematic review of the scientific literature that addresses SMT from a logistics and management perspective. A comprehensive summary was achieved by employing broad search terms, and an in-depth analysis was performed to provide an overview of the current state-of-the-art SMT research. Concerning the limitations of the work, two points should be mentioned: The database search was conducted exclusively in the Web of Science. The papers identified in this way were subjected to a forward and backward search, through which six further papers were identified. However, the possibility that further literature on SMT exists cannot be excluded entirely. Furthermore, we limited the review's scope to references that explicitly focus on synchromodal transportation. Therefore, the possibilities of transforming approaches from other related research fields, such as the physical internet or digitalization of the transport sector, are not investigated.

The review's main findings can be concluded according to the research questions (RQ).

Regarding RQ 1.1, SMT can be seen as an active topic that has attracted the interest of researchers worldwide, but especially in Europe, in the past years. Starting with mainly qualitative research, the focus shifted to mathematical planning problems over the years. To organize the literature and answer RQ 1.2, a comprehensive taxonomy of five dimensions and 13 categories for qualitative and quantitative papers is developed. Consequently, an extensive evaluation of the papers' content is achieved, connections between the papers are established, and research results are consolidated. Furthermore, the two research approaches are compared, and commonalities and differences are identified. The results reveal a mixed picture, with high consistency in geographical areas of SMT implementation and suitable modeling of operational disruptions and uncertainties but little alignment in the forms of collaboration and synchromodal transportation network organization. Finally, future research fields, namely business, legal, technological, modeling, and awareness of synchromodal transportation (RQ 1.3), are disclosed to foster the successful long-term implementation of synchromodal transportation.

Author Contributions: The authors confirm contribution to the paper as follows: study conception and design: J.R., R.E. and F.W.; data collection: F.W.; analysis and interpretation of results: J.R. and F.W.; draft manuscript preparation: J.R. and F.W. All authors reviewed the results and approved the final version of the manuscript.

Funding: We acknowledge support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) and the Open Access Publishing Fund of Technical University of Darmstadt.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Eurostat-Statistics Explained. Climate Change-Driving Forces. 2021. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Climate_change_-_driving_forces (accessed on 19 August 2022).
2. Eurostat-Statistics Explained. Freight Transport Statistics-Modal Split. 2022. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Freight_transport_statistics_-_modal_split (accessed on 19 August 2022).
3. Tavasszy, L.; Janssen, R.; van der Lugt, L.; Hagdorn, L. (Eds.) *Verkenning Synchromodaal Transportsysteem*; TNO: Delft, The Netherlands, 2010.
4. Agbo, A.A.; Li, W.; Atombo, C.; Lodewijks, G.; Zheng, L. Feasibility study for the introduction of synchromodal freight transportation concept. *Cogent Eng.* **2017**, *4*, 1–25. [CrossRef]
5. SteadieSeifi, M.; Dellaert, N.; Nuijten, W.; Van Woensel, T.; Raoufi, R. Multimodal freight transportation planning: A literature review. *Eur. J. Oper. Res.* **2014**, *233*, 1–15. [CrossRef]
6. Pfoser, S.; Treiblmaier, H.; Schauer, O. Critical Success Factors of Synchromodality: Results from a Case Study and Literature Review. *Transp. Res. Procedia* **2016**, *14*, 1463–1471. [CrossRef]
7. Ambra, T.; Caris, A.; Macharis, C. Towards freight transport system unification: Reviewing and combining the advancements in the physical internet and synchromodal transport research. *Int. J. Prod. Res.* **2019**, *57*, 1606–1623. [CrossRef]
8. Acero, B.; Saenz, M.J.; Luzzini, D. Introducing synchromodality: One missing link between transportation and supply chain management. *J. Supply Chain Manag.* **2022**, *58*, 51–64. [CrossRef]
9. Delbart, T.; Molenbruch, Y.; Braekers, K.; Caris, A. Uncertainty in Intermodal and Synchromodal Transport: Review and Future Research Directions. *Sustainability* **2021**, *13*, 3980. [CrossRef]
10. Pfoser, S.; Kotzab, H.; Bäumler, I. Antecedents, mechanisms and effects of synchromodal freight transport: A conceptual framework from a systematic literature review. *Int. J. Logist. Manag.* **2021**, *33*, 190–213. [CrossRef]
11. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
12. Denyer, D.; Tranfield, D. Producing a Systematic Review. In *D. A. Buchanan & A. Bryman (Eds.), The Sage Handbook of Organizational Research Methods*; Sage Publications Ltd.: Thousand Oaks, CA, USA, 2009; pp. 671–689.
13. Mayring, P. Qualitative Content Analysis: Theoretical Background and Procedures. In *Approaches to Qualitative Research in Mathematics Education*; Springer: Dordrecht, The Netherlands, 2015; pp. 365–380.
14. Seuring, S.; Gold, S. Conducting content-analysis based literature reviews in supply chain management. *Supply Chain Manag. Int. J.* **2012**, *17*, 544–555. [CrossRef]
15. Durach, C.F.; Kembro, J.; Wieland, A. A New Paradigm for Systematic Literature Reviews in Supply Chain Management. *J. Supply Chain Manag.* **2017**, *53*, 67–85. [CrossRef]
16. Kitchenham, B.; Charters, S. Guidelines for Performing Systematic Literature Reviews in Software Engineering. 2007. Available online: https://www.elsevier.com/__data/promis_misc/525444systematicreviewsguide.pdf (accessed on 19 August 2022).
17. Tavasszy, L.; Behdani, B.; Konings, R. Intermodality and Synchromodality. In *Ports and Networks*; Routledge: London, UK, 2017; pp. 251–266. [CrossRef]
18. Alons-Hoen, K.; Somers, G.; van Duin, R. The current state of Synchromodality: An application of a synchromodal maturity model on case studies. *LOGISTIEK Tijdschr. Voor Toegep. Logist.* **2019**, *8*, 116–131.
19. Brümmerstedt, K.; Meyer-Van Beek, H.; Münsterberg, T. *Comparative Analysis of Synchromodality in Major European Seaports*; epubli GmbH: Berlin/Heidelberg, Germany, 2017.
20. Tsertou, A.; Amditis, A.; Latsa, E.; Kanellopoulos, I.; Kotras, M. Dynamic and Synchromodal Container Consolidation: The Cloud Computing Enabler. *Transp. Res. Procedia* **2016**, *14*, 2805–2813. [CrossRef]
21. Buiel, E.; Visschedeijk, G.; Lebesque, L.; Lucassen, I.; van Riessen, B.; van Rijn, A.; te Brake, G.M. Synchro Mania-Design and Evaluation of a Serious Game Creating a Mind Shift in Transport Planning. 2015. Available online: https://www.researchgate.net/publication/283085753 (accessed on 19 August 2022).
22. Kurapati, S.; Kourounioti, I.; Lukosch, H.; Tavasszy, L.; Verbraeck, A. Fostering Sustainable Transportation Operations through Corridor Management: A Simulation Gaming Approach. *Sustainability* **2018**, *10*, 455. [CrossRef]
23. Giusti, R.; Manerba, D.; Bruno, G.; Tadei, R. Synchromodal logistics: An overview of critical success factors, enabling technologies, and open research issues. *Transp. Res. Part E Logist. Transp. Rev.* **2019**, *129*, 92–110. [CrossRef]
24. Reis, V. Should we keep on renaiming a +35-year-old baby? *J. Transp. Geogr.* **2015**, *46*, 173–179. [CrossRef]
25. Perboli, G.; Musso, S.; Rosano, M.; Tadei, R.; Godel, M. Synchro-Modality and Slow Steaming: New Business Perspectives in Freight Transportation. *Sustainability* **2017**, *9*, 1843. [CrossRef]

26. De Juncker, M.; Huizinger, D.; Del Ortega Vecchyo, M.R.; Phillipson, F.; Sangers, A. Framework of Synchromodal Transportation Problems. In Proceedings of the 8th International Conference on Computational Logistics, Southampton, UK, 18–20 October 2017; Volume 10572, pp. 383–403.
27. Van Riessen, B.; Negenborn, R.R.; Dekker, R. Synchromodal Container Transportation: An Overview of Current Topics and Research Opportunities. In Proceedings of the 6th International Conference on Computational Logistics, Delft, The Netherlands, 23–25 September 2015; Volume 9335, pp. 386–397. [CrossRef]
28. Talpur, M.A.H.; Napiah, M.; Chandio, I.A.; Khahro, S.H. Transportation Planning Survey Methodologies for the Proposed Study of Physical and Socio-economic Development of Deprived Rural Regions: A Review. *Mod. Appl. Sci.* **2012**, *6*, 1. [CrossRef]
29. Bol Raap, W.; Iacob, M.-E.; van Sinderen, M.; Piest, S. An Architecture and Common Data Model for Open Data-Based Cargo-Tracking in Synchromodal Logistics. In *On the Move to Meaningful Internet Systems: OTM 2016 Conferences*; Debruyne, C., Panetto, H., Meersman, R., Dillon, T., Kühn, E., O'Sullivan, D., Ardagna, C.A., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 327–343. ISBN 978-3-319-48471-6.
30. Khakdaman, M.; Rezaei, J.; Tavasszy, L.A. Shippers' willingness to delegate modal control in freight transportation. *Transp. Res. Part E Logist. Transp. Rev.* **2020**, *141*, 102027. [CrossRef]
31. Hofman, W. Control Tower Architecture for Multi- and Synchromodal Logistics with Real Time Data. In Proceedings of the 5th Information Systems, Logistics, and Supply Chain International Conference 2014, Breda, The Netherlands, 24–27 August 2014.
32. Giusti, R.; Manerba, D.; Tadei, R. Smart Steaming: A New Flexible Paradigm for Synchromodal Logistics. *Sustainability* **2021**, *13*, 4635. [CrossRef]
33. Giusti, R.; Iorfida, C.; Li, Y.; Manerba, D.; Musso, S.; Perboli, G.; Tadei, R.; Yuan, S. Sustainable and De-Stressed International Supply-Chains through the SYNCHRO-NET Approach. *Sustainability* **2019**, *11*, 1083. [CrossRef]
34. Koop, A.; Moock, H. *Lineare Optimierung–Eine Anwendungsorientierte Einführung in Operations Research*; Springer: Berlin/Heidelberg, Germany, 2018; ISBN 978-3-662-56140-9.
35. Kapetanis, G.N.; Psaraftis, H.N.; Spyrou, D. A Simple Synchro–Modal Decision Support Tool for the Piraeus Container Terminal. *Transp. Res. Procedia* **2016**, *14*, 2860–2869. [CrossRef]
36. Xu, Y.; Cao, C.; Jia, B.; Zang, G. Model and Algorithm for Container Allocation Problem with Random Freight Demands in Synchromodal Transportation. *Math. Probl. Eng.* **2015**, *2015*, 986152. [CrossRef]
37. Batarlienė, N.; Šakalys, R. Mathematical Model for Cargo Allocation Problem in Synchromodal Transportation. *Symmetry* **2021**, *13*, 540. [CrossRef]
38. Guo, W.; Atasoy, B.; van Blokland, W.B.; Negenborn, R.R. Global synchromodal transport with dynamic and stochastic shipment matching. *Transp. Res. Part E Logist. Transp. Rev.* **2021**, *152*, 102404. [CrossRef]
39. Zhang, M.; Pel, A. Synchromodal hinterland freight transport: Model study for the port of Rotterdam. *J. Transp. Geogr.* **2016**, *52*, 1–10. [CrossRef]
40. Lin, X.; Negenborn, R.R.; Lodewijks, G. Towards Quality-aware Control of Perishable Goods in Synchromodal Transport Networks. *IFAC-PapersOnLine* **2016**, *49*, 132–137. [CrossRef]
41. Nabais, J.L.; Negenborn, R.R.; Carmona-Benítez, R.; Botto, M.A. (Eds.) *Cooperative Relations among Intermodal Hubs and Transport Providers at Freight Networks Using an MPC Approach*; Springer International Publishing: Cham, Switzerland, 2015; ISBN 978-3-319-24263-7.
42. Guo, W.; Atasoy, B.; van Blokland, W.B.; Negenborn, R.R. A dynamic shipment matching problem in hinterland synchromodal transportation. *Decis. Support Syst.* **2020**, *134*, 113289. [CrossRef]
43. Rivera, A.E.P.; Mes, M.R.K. (Eds.) *Service and Transfer Selection for Freights in a Synchromodal Network*; Springer International Publishing: Cham, Switzerland, 2016; ISBN 978-3-319-44895-4.
44. Rivera, A.E.P.; Mes, M.R.K. Integrated scheduling of drayage and long-haul operations in synchromodal transport. *Flex. Serv. Manuf. J.* **2019**, *31*, 763–806. [CrossRef]
45. Rivera, A.E.P.; Mes, M.R.K. Anticipatory scheduling of synchromodal transport using approximate dynamic programming. *Ann. Oper. Res.* **2022**, 1–35. [CrossRef]
46. Ambra, T.; Caris, A.; Macharis, C. Should I Stay or Should I Go? Assessing Intermodal and Synchromodal Resilience from a Decentralized Perspective. *Sustainability* **2019**, *11*, 1765. [CrossRef]
47. Yee, H.; Gijsbrechts, J.; Boute, R. Synchromodal transportation planning using travel time information. *Comput. Ind.* **2021**, *125*, 103367. [CrossRef]
48. Resat, H.G.; Turkay, M. A discrete-continuous optimization approach for the design and operation of synchromodal transportation networks. *Comput. Ind. Eng.* **2019**, *130*, 512–525. [CrossRef]
49. Guo, W.; Atasoy, B.; Negenborn, R.R. Global synchromodal shipment matching problem with dynamic and stochastic travel times: A reinforcement learning approach. *Ann. Oper. Res.* **2022**, 1–32. [CrossRef]
50. Guo, W.; Atasoy, B.; van Blokland, W.B.; Negenborn, R.R. Anticipatory approach for dynamic and stochastic shipment matching in hinterland synchromodal transportation. *Flex. Serv. Manuf. J.* **2021**, *34*, 483–517. [CrossRef] [PubMed]
51. Van Riessen, B.; Negenborn, R.R.; Dekker, R. Real-time container transport planning with decision trees based on offline obtained optimal solutions. *Decis. Support Syst.* **2016**, *89*, 1–16. [CrossRef]
52. Crainic, T.G.; Giusti, R.; Manerba, D.; Tadei, R. The Synchronized Location-Transshipment Problem. *Transp. Res. Procedia* **2021**, *52*, 43–50. [CrossRef]

53. Van Riessen, B.; Negenborn, R.R.; Dekker, R. The Cargo Fare Class Mix problem for an intermodal corridor: Revenue management in synchromodal container transportation. *Flex. Serv. Manuf. J.* **2017**, *29*, 634–658. [CrossRef]
54. Van Riessen, B.; Mulder, J.; Negenborn, R.R.; Dekker, R. Revenue management with two fare classes in synchromodal container transportation. *Flex. Serv. Manuf. J.* **2021**, *33*, 623–662. [CrossRef]
55. Larsen, R.B.; Atasoy, B.; Negenborn, R.R. Model predictive control for simultaneous planning of container and vehicle routes. *Eur. J. Control* **2020**, *57*, 273–283. [CrossRef]
56. Zhang, Y.; Atasoy, B.; Negenborn, R.R. Preference-Based Multi-Objective Optimization for Synchromodal Transport Using Adaptive Large Neighborhood Search. *Transp. Res. Rec. J. Transp. Res. Board* **2021**, *2676*, 71–87. [CrossRef]
57. De Koning, W.J.; Phillipson, F.; Chiscop, I. Simulation Approach for Container Assignment Under Uncertainty. In *Computational Logistics*; Lalla-Ruiz, E., Mes, M.R.K., Voß, S., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 616–630. ISBN 978-3-030-59746-7.
58. Behdani, B.; Fan, Y.; Wiegmans, B.; Zuidwijk, R. Multimodal schedule design for synchromodal freight transport systems. *Eur. J. Transp. Infrastruct.* **2016**, *16*, 424–444. [CrossRef]
59. Larsen, R.B.; Baksteen, R.; Atasoy, B.; Negenborn, R.R. Secure Multi-party Co-planning of Barge Departures. *IFAC-PapersOnLine* **2021**, *54*, 335–341. [CrossRef]
60. Li, L.; Negenborn, R.R.; De Schutter, B. Distributed model predictive control for cooperative synchromodal freight transport. *Transp. Res. Part E Logist. Transp. Rev.* **2017**, *105*, 240–260. [CrossRef]
61. De Juncker, M.; Phillipson, F.; Bruijns, L.A.M.; Sangers, A. (Eds.) *Optimising Routing in an Agent-Centric Synchromodal Network with Shared Information*; Springer International Publishing: Cham, Switzerland, 2018; ISBN 978-3-030-00897-0.
62. Giusti, R.; Manerba, D.; Tadei, R. Multiperiod transshipment location–allocation problem with flow synchronization under stochastic handling operations. *Networks* **2021**, *78*, 88–104. [CrossRef]
63. Zweers, B.G.; Bhulai, S.; van der Mei, R.D. Planning hinterland container transportation in congested deep-sea terminals. *Flex. Serv. Manuf. J.* **2021**, *33*, 583–622. [CrossRef]
64. Kalicharan, K.; Phillipson, F.; Sangers, A. Cutting Planes for Solving Logistic Flow Problems. In *Computational Logistics*; Lalla-Ruiz, E., Mes, M.R.K., Voß, S., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 569–583. ISBN 978-3-030-59746-7.
65. Qu, W.; Rezaei, J.; Maknoon, Y.; Tavasszy, L. Hinterland freight transportation replanning model under the framework of synchromodality. *Transp. Res. Part E Logist. Transp. Rev.* **2019**, *131*, 308–328. [CrossRef]
66. Li, S.; Negenborn, R.R.; Liu, J. Stimulating Inland Waterway Transport Between Seaports and the Hinterland from a Coordination Perspective. In *Optimising Routing in an Agent-Centric Synchromodal Network with Shared Information*; de Juncker, M., Phillipson, F., Bruijns, L.A.M., Sangers, A., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 67–85. ISBN 978-3-030-00897-0.
67. Del Vecchyo, M.R.O.; Phillipson, F.; Sangers, A. Alternative Performance Indicators for Optimizing Container Assignment in a Synchromodal Transportation Network. In *Computational Logistics, Proceedings of the 9th International Conference, ICCL 2018, Vietri Sul Mare, Italy, 1–3 October 2018*; Cerulli, R., Ed.; Springer International Publishing AG: Cham, Switzerland, 2018; pp. 316–330. ISBN 9783030008987.
68. Dobrkovic, A.; Iacob, M.-E.; van Hillegersberg, J. Maritime pattern extraction and route reconstruction from incomplete AIS data. *Int. J. Data Sci. Anal.* **2018**, *5*, 111–136. [CrossRef]
69. Dong, C.; Boute, R.; McKinnon, A.; Verelst, M. Investigating synchromodality from a supply chain perspective. *Transp. Res. Part D Transp. Environ.* **2018**, *61*, 42–57. [CrossRef]
70. Lemmens, N.; Gijsbrechts, J.; Boute, R. Synchromodality in the Physical Internet–dual sourcing and real-time switching between transport modes. *Eur. Transp. Res. Rev.* **2019**, *11*, 19. [CrossRef]
71. Zahid, T.; Gillani, F.; Ghafoor, U.; Bhutta, M.R. Synchromodal Transportation Analysis of the One-Belt-One-Road Initiative Based on a Bi-Objective Mathematical Model. *Sustainability* **2022**, *14*, 3201. [CrossRef]
72. Mes, M.R.K.; Iacob, M.-E. Synchromodal Transport Planning at a Logistics Service Provider. In *Logistics and Supply Chain Innovation*; Zijm, H., Klumpp, M., Clausen, U., ten Hompel, M., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 23–36. ISBN 978-3-319-22287-5.
73. Farahani, N.Z.; Noble, J.S.; Klein, C.M.; Enayati, M. A decision support tool for energy efficient synchromodal supply chains. *J. Clean. Prod.* **2018**, *186*, 682–702. [CrossRef]