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Exploring Multi-Agent Systems for Intermodal Freight Fleets: Literature-based Justification of a New Concept

Research Paper

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Abstract. Freight transportation is increasingly connected with the automation of fleet assets by intelligent systems. This study emerges from the consortium research project Gaia-X 4 ROMS, which aims to develop a comprehensive approach for smart freight fleets in the field of parcel deliveries. Within this project, a novel type of multi-agent system (MAS) for the management of freight fleets is being developed. To determine the state of prior research and recent developments in this field, a systematic literature review was conducted and presented herein. The findings of the review demonstrate a lack of applied solutions in this topic, highlighting the need for a novel approach. Accordingly, a first framework for the envisioned multi-agent system, as conceptualized within the consortium research project, is presented in this work, serving as a basis for subsequent design phases.

Keywords: Systematic Literature Review, Multi-Agent System, Intelligent Logistics, Smart Freight Fleet, Consortium Research

1 Introduction

The e-commerce business reached a record sales revenue with more than \$ 5 trillion in 2021 globally (Chevalier 2022), driving a continuous parcel delivery growth across nations. In Germany, for instance, the number of business-to-consumer (B2C) parcels delivered has increased by 16.6 per cent in the same year compared to 2020, leading to 15 million parcels delivered per day (BIEK 2022). Parcel delivery chains are composed of different freight transport legs (i.e., first-mile, long-haul, and last mile transport) and involve various operators (e.g., dispatcher, customs, delivery man) and resources (e.g., vans, trucks, trailers, delivery robots). A higher degree of automation in the parcel delivery chain is seen as an opportunity for logistics companies to cope with the enormous quantities of parcel deliveries within logistics networks (Dekhne et al. 2019). A central software for an automated management of the involved actors in intermodal parcel deliveries is often not applicable due to a fragmented business industry and the complex interdependencies inherent in such transportation systems. Instead, a multi-agent-based approach could be used in which each of the distributed actors involved in the different legs of the transport chain is represented by an autonomous software agent. The software agent then decides for an actor whether and when a task is executed. In this context, a MAS enables the decomposition of complex problems and efficient distribution of both

data and control across physical boundaries (Jennings 2000, Wooldridge & Ciancarini 2001). However, the multi-agent-based management of parcel deliveries while using state-of-the-art freight fleet resources like delivery robots and telematic-equipped trailers is a sparsely investigated topic. In this light, the consortium research project Gaia-X 4 ROMS (Remote Operation for Automated and Connected Mobility Services) (Gaia-X 4 Future Mobility n.d.) has been established. The consortium research project seeks further to contribute to the development of federated data ecosystems promoting data sovereignty and fair competition for distributed participants involved in the provision and consumption of data (Braud et al. 2021).

To obtain an overview of existing solutions for MAS in freight fleet management, several reviews and surveys were identified. This includes literature reviews conducted by Davidsson et al. (2005) and Falco & Robiolo (2019), indicating a lack of research in the field of MAS that were applied to automate processes in the transportation sector. Further, while academia has addressed MAS for city logistics (Taniguchi et al. 2020) or urban mobility (de Gauna et al. 2020), solutions for managing an intermodal freight fleet in its entirety, as it is planned in the consortium research project, remain yet scarce. To gain precise and holistic knowledge of the topic addressed, a systematic literature review was deemed necessary. The literature review revealed a research gap in this field and justifies a novel MAS concept for freight fleet management which is presented in this paper. Overall, the following research questions (RQ) guide the initial phases for a dedicated MAS solution:

RQ1: What is the current state of research on the use of multi-agent systems for managing intermodal freight fleets?

RQ2: To what extent have these systems been implemented and applied in practice, hence what maturity level did they reach?

RQ3: Can a concept for a multi-agent system for managing intermodal freight fleets be justified by the findings of the literature review?

To answer the research questions, the remainder of the paper is organized as follows. In Section 2, we establish a background of the topic addressed and present relevant definitions. Afterwards, in Section 3, we introduce the approach for our systematic literature review as one iteration in the design science research approach that is applied in our consortium research project. Subsequently, in Section 4, we present the findings of the literature review and propose a novel concept of a MAS for intermodal freight fleet management. Section 5 encompasses a discussion of the results and states implications for the research consortium process. Lastly, in Section 6, we emphasize the limitations of our paper, conclude our work, and provide an outlook for future research.

2 Background

MASs and transport logistics management have been the focus of significant attention in recent years, and their broad applicability has resulted in a range of definitions that varies among different disciplines. To provide a comprehensive understanding, it is important to outline the definitions of both MASs and transport logistics.

2.1 Multi-Agent Systems

MASs are composed of several autonomous agents (Pitt 2021). According to Pitt (2021), each autonomous agent in a MAS represents a human being or an organization and is responsible for undertaking certain actions on its behalf in an intelligent way while continuously taking input from the environment or other agents into account. However, on a lower level of abstraction, an autonomous agent is “an embedded software process which encapsulates some notion of state and communicates with others by message passing” (Pitt 2021, p.18). Different architectures exist that can be used to develop autonomous agents. For example, when following the BDI architecture, an agent consists of a control loop with three states: belief revision (belief), option generation (desire), and action selection (intention) (Pitt 2021). Wahlster (2017) differentiates between autonomous systems that are robots with physical sensors and actors, and those that are software agents (or softbots) acting solely in digital environments. Apart from control loops which are necessary for self-regulation, autonomous systems may consist of actors, sensors, a knowledge base and mechanisms for learning, optimization, collaboration, and communication (Wahlster 2017).

2.2 Intermodal Freight Fleets, Digitalization, and Software Agents

Road freight transportation bridges the physical distances between shippers (e.g., retailer) and consignees (e.g., consumers) for delivering freight (e.g., finished products packaged in parcels) in the B2C business. A closer look into the transport chain for parcel deliveries reveals three transport stages: a first-mile transport from the shipper to a depot, a long-haul transport between two depots, and a last-mile transport from the depot to another consignee (Brabänder & Braun 2020). This situation is accompanied by an intense technological transformation of the road freight sector focusing on data-driven business opportunities leading to intermodal fleet operations combining freight fleets, customer orders, and the operational activities of both transport and fleet operators (Akac et al. 2020, Farquharson et al. 2021). The wave of digital innovations consequently aims at the automation of road freight transportation addressing: (1) mobile delivery robots that can navigate autonomously through urban areas for the first- and last-mile transport of parcels and that can track their own status and those of the parcels (Asdecker 2020), (2) autonomous trucks for the long-haul transports between depots mostly on highways (Sternberg et al. 2020), (3) telematic units that can continuously track the status of trucks, swap bodies, trailers, and their load during long-haul transports (Heinbach et al. 2022c), (4) intelligent data services that can be used to improve forecasts and planning (Birkel et al. 2020), and (5) digital platforms to exchange road freight orders and transport orders between platform participants and to optimize order assignments (Heinbach et al. 2022a). MASs are especially applicable for the automation of the order management in intermodal freight fleets, because a multi-agent-based approach does not include a central control instance and can thus better cope with the fragmented business industry in the transport logistics sector.

3 Research Methods

This section presents a comprehensive outline of the methodologies employed in this study, detailing the systematic approach taken in the consortium research project for the literature review and the development of the new MAS concept.

3.1 Design Science Research Process (DSRP) of a Consortium Research Project

The research of the MAS for freight fleet management, as part of the consortium research project, employs a consortium research methodology that is structurally aligned to the Design Science Research Process (DSRP) framework, following Österle & Otto (2010). One of the key advantages of this approach is that it facilitates knowledge exchange with the practitioner community. To navigate the development, the DSRP as proposed by Peffers et al. (2007) provides a basic framework for designing and evaluating solutions to complex problems. The methodology consists of several iterative steps as depicted in Figure 1. The outcomes of the research within the consortium research project, encompassing the first two steps, are presented in this work.

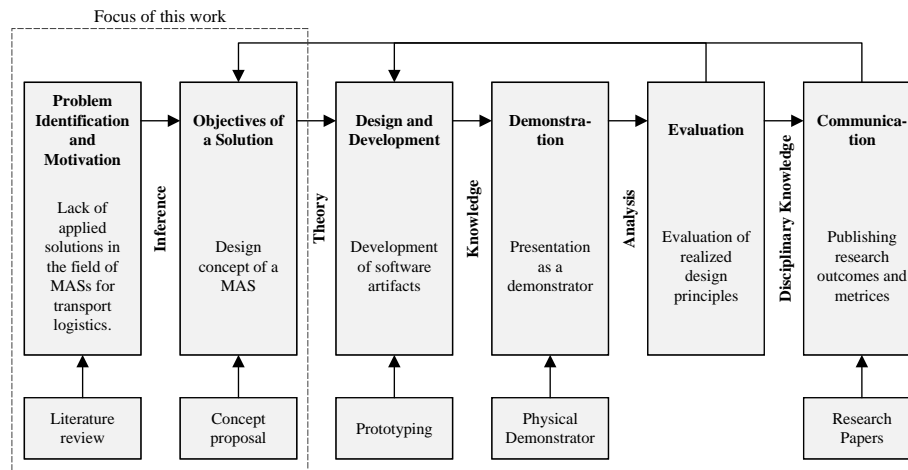


Figure 1. Design science research process (DSRP) model as described by Peffers et al. (2007).

In the methodology of evidence-based software engineering, a systematic literature review aims to accumulate all evidence on a research question (Kitchenham et al. 2009), but also identifies research gaps (Kitchenham 2004), and most notably aids the decision-making process in the development of software artifacts (Dyba et al. 2005). In the context of our consortium research project, the systematic literature review in this work corroborates our research approach and demonstrates the absence of prior investigations in this field, thus highlighting the necessity for a novel MAS concept for freight fleet management. Due to the scope of our project on the logistics sector, which focuses generally on the transport of goods and not on the transport of humans

(Muchna et al. 2017), we did not include papers that describe a human-centered MAS for the management of passenger traffic. In the second step, the research requirements and basic design features of the system were gathered in close collaboration with practitioners, following the recommended procedure of Sonnenberg & vom Brocke (2012) and the closely related Action Design Research (ADR) methodology proposed by Sein et al. (2011). In this process, the relevant technologies and actors were identified. As a result, concepts were derived for the software agents to represent the various actors and resources with their respective responsibilities in a given transport chain. These concepts for the different types of software agents were iteratively refined and evaluated with the practitioners. For this end, the online collaboration tool Miro was used (Miro n.d.). In addition, the importance of integrating state-of-the-art technology such as delivery robots and telematic-enabled trailers as well as having a sovereign data exchange within a dataspace in the broader context of Gaia-X were identified as further critical objectives of the research project (Heinbach et al. 2022b).

3.2 Methodology used for the Systematic Literature Review

To answer RQ1 using empirical evidence and facilitate knowledge advancement and further developments, our literature review must prioritize transparency and replicability throughout the rigor review process, thereby mitigating potential bias and ensuring comprehensive research outcomes. Thus, to adhere to these principles, a research protocol was established (Snyder 2019, Tranfield et al. 2003).

To precisely address the subject of MASs, and to ensure that only relevant studies are included while avoiding those for e.g., agent-based simulations, the string *multi-agent* was selected. To further narrow down the application area of the MAS, the string *fleet management* was incorporated. Additionally, to focus on freight and differentiate from other types of transportation (e.g., public transport), a third string *freight* was introduced. Hence, to ensure a comprehensive search that aligns to our research question, the search term *multi-agent AND (fleet management) AND freight* was selected.

For the purpose of a comprehensive literature review, several electronic databases were identified and included in the search process, namely SpringerLink, ScienceDirect, AISel, Wiley, IEEE, ACM, JSTOR and Scopus (Gusenbauer & Haddaway 2020, Charband & Navimipour 2016, de Gauna et al. 2020). In accordance with Kitchenham (2004), primary studies of all types of outlets are included in the search to counter a possible publication bias. EndNote serves as the primary reference management tool utilized for this systematic literature review, complemented by Excel for quantitative analysis and reporting of the search process at each step. To include all research evidence with regard to the initially formulated research question, the primary studies are not filtered by year of publication. As suggested by Kitchenham (2004), no additional language filtering was conducted in order to avoid a language bias (Rothstein et al. 2005). After retrieving all search results, studies are filtered by accessibility of full text in the first step, followed by a successive relevance assessment of titles and abstracts with respect to RQ1, i.e., the relevance with respect to the development of MASs for freight fleet management. To prevent inadvertent exclusion of relevant research, broader inclusion criteria were applied when screening the titles and abstract. Hence, all studies covering concepts

of intelligent systems or recent innovations for transportation problems were included. Eligible studies undergo a rigorous full-text evaluation to ensure stricter inclusion criteria are met, allowing only those studies to be included that explicitly address MASs for transportation problems. Additionally, related approaches like agent-based modeling are excluded, and only studies concerning transport logistics and road-based transport in the transport chain are included in order to comply with RQ1 and the scopes of the research consortium project.

4 Literature Review Results and Arising Concept Proposal

Building upon the preceding sections that laid out the context and methodology, this section endeavors to deliver the outcomes of the literature review and proposes a novel concept of using a MAS for freight fleet management, which was developed in the consortium research project. This section follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher et al. 2009, Liberati et al. 2009) that provides a standardized reporting guideline ensuring the completeness and transparency of systematic reviews.

4.1 Results of the Systematic Literature Review

Study selection process Figure 2 illustrates the process of data selection in this study based on the research protocol as defined in Section 3. In the first step, 4,414 studies were identified by searching the online databases with the defined search string. The 130 studies that emerged from the sequential process of screening the titles and abstracts were then subjected to a full-text assessment to determine their eligibility in addressing research question RQ1, leading to 24 included studies for the review¹. The excluded reports of this last step were subsequently categorized based on their respective reasons for exclusion, as listed in Figure 2.

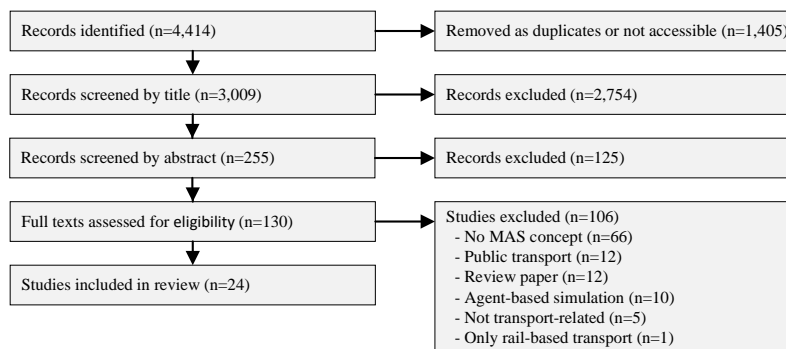


Figure 2. Flow diagram of the literature screening process, based on Page et al. (2021).

¹ Comprehensive bibliographic information relating to each subsequent phase of the screening process, following the initial title screening, can be accessed here: bit.ly/WI2023_397

Data Synthesis To investigate the temporal trends in the research topic, the publication dates of each study included in the literature review were extracted. The distribution of these dates was analyzed to identify patterns of scholarly interest in the subject over time. Even though no filtering based on the year of publication was applied to the studies, the earliest study identified in the review dates back to 1994, suggesting that the subject of MASs for fleet management is a relatively recent research topic. Although the limited number of studies prevents definitive conclusions regarding the temporal trends in the field, the analysis underscores a persistent scholarly interest in the subject since 2005.

Data Abstraction This part aims to assess the current state of research and maturity of MAS solutions in freight fleet management (RQ1, RQ2). Further, the concepts to be extracted from the individual studies were delineated based on the requirements of the consortium research project. Firstly, the assessment focused on determining whether the specific study pertains to the domain of logistics, specifically parcel delivery, as this is the main focus of the consortium research project. Additionally, it was assessed whether the agents act as representatives of the supply chain entities (e.g., trailers, depots) to allow for a direct agent-based representation and responsibility of a physical entity. The prospect of physical distribution of the system is also contemplated, as the consortium research project necessitates not only the deployment of agents on a single server, but their migration capability of agents to fleet assets, such as delivery robots. As stated before, the transport chain for parcel delivery comprises the stages of first- and last-mile delivery, as well as the long-haul transport between depots. To comprehend and efficiently respond to the complex interdependencies of logistics processes at a system-level, it is essential to adopt a holistic perspective that considers all segments of the transport chain as a unified system. Accordingly, these three transport chain segments were defined as the concepts to be extracted from the literature. Closely tied to this is the concept of intermodality, as presented in Section 2.2. Lastly, the concept of maturity was introduced as similarly done by Davidsson et al. (2005). In this work, the maturity of a MAS is assessed based on three stages: (1) proposed concept or ontology, (2) implemented or tested MAS, (3) the deployment of a MAS in an applied fleet management system. The abstracted data was then aggregated into a concept matrix as proposed by Webster & Watson (2002), shown in Table 1. From the high-level perspective provided in Table 1 it is notable that there is a low density in concepts abstracted from the studies. Of the 24 studies surveyed, only ten explicitly combine agents with transport entities. Other approaches consider the agents as representatives of regions (Dorer & Calisti 2005*a,b*), or specific tasks, such as optimization (Miliauskas 2022), or as representatives of companies and parties (van der Putten et al. 2006, Robu et al. 2008, Teo et al. 2012, 2014). The solution of Maestro et al. (2021) is representing carriers by virtual organizations of agents, that are each individually responsible for certain tasks, e.g., optimization or urban traffic information. The majority of the papers that did not explicitly address parcel delivery consider rather focused topics, e.g., the pickup-and-delivery problem (Kozłak 2007) or delivery in the presence of flooding events (de Oliveira et al. 2017) without detailing the nature of goods. Other works state different types of goods, such as art, furniture and computers (Falk et al. 1994), or containers (Wojtusiak et al. 2012).

Table 1. Concept matrix of the analyzed literature according to Webster & Watson (2002).

Articles	Concepts							
	Agents representing physical resources	Distributed system	Parcel delivery	Intermodality	Part of transport chain			Maturity level
					First mile	Long-haul	Last mile	
Boussier et al. (2009)	•		•				•	1
Dorer & Calisti (2005a)		•			•		•	3
Dorer & Calisti (2005b)					•		•	3
Elfazziki et al. (2009)		•					•	2
Falk et al. (1994)	•				•		•	2
Funk et al. (1999)	•	•		•	•	•	•	2
Giret et al. (2018)	•	•	•	•	•		•	2
Gómez-Marín et al. (2018)	•		•		•		•	1
Holmgren et al. (2012)				•	•		•	2
Koźlak (2007)	•				•		•	2
Los et al. (2020)	•		•		•		•	2
Los et al. (2022)	•		•		•		•	2
Maestro et al. (2021)		•					•	1
Mes et al. (2008)	•				•		•	2
Mes et al. (2013)	•				•		•	2
Miliauskas (2022)		•						1
de Oliveira et al. (2017)							•	2
van der Putten et al. (2006)					•		•	2
Robu et al. (2008)					•		•	2
Sitek et al. (2014)				•			•	2
Stinson & Mohammadian (2022)				•	•	•	•	2
Teo et al. (2012)			•		•		•	2
Teo et al. (2014)			•		•		•	2
Wojtusiak et al. (2012)		•				•		2
Total	10	7	7	5	17	3	22	

Further fields of interest in the analyzed literature were bidding and auction mechanisms (Los et al. 2020, 2022, Mes et al. 2008, 2013, van der Putten et al. 2006, Robu et al. 2008), ontologies (Giret et al. 2018, Miliuskas 2022) or assessing the impact of transport measures on MAS-based delivery systems (Holmgren et al. 2012, Teo et al. 2012, 2014). Moreover, several works take into account the influence of traffic on the distribution of urban goods (Boussier et al. 2009, Gómez-Marín et al. 2018, Koźlak 2007). Only two studies reached the highest stage of a deployed system (Maturity 3), namely the two contributions by Dorer & Calisti (2005*a,b*), in which the Living Systems Adaptive Transportation Networks (LS/ATN) framework is proposed that is deployed with one of the logistics partners (Dorer & Calisti 2005*b*). However, the system is deployed in a centralized manner, integrating into an existing traffic management system (Dorer & Calisti 2005*b*). It has to be noted however, that Dorer & Calisti (2005*a*) additionally present tests for a physically distributed agent-based approach. Although not assigned to the highest maturity stage, the closely connected works of van der Putten et al. (2006) and Robu et al. (2008) were developed in close collaboration with the European logistics service provider Vos logistics, with plans for deployment of the proposed MAS (van der Putten et al. 2006). Another approach of potential significance was formulated by Funk et al. (1999), which covers a holonic MAS for rail-based inter-depot logistics and road-based pickups and deliveries. Yet, this solution was proposed only at the stage of a prototypic simulation. In view of RQ1, it can thus be concluded that there is a high research interest in MAS for fleet management. Nevertheless, the current literature predominantly focuses on specific problems, the last-mile delivery for instance, or particular mechanisms such as auctioning or bidding, rather than considering the complete transport chain on a system level as done within our consortium research project. Further, concerning RQ2 it can be summarized that the majority of the proposed MAS were at a stage in which tests or simulations were presented (Maturity 2). However, only two studies reached the highest stage of a deployed system (Maturity 3).

4.2 Proposition of a Novel Concept

The previous section revealed the lack of applied MAS solutions for the integrated and automated management of an intermodal freight fleet consisting of vehicles for the first-mile, long-haul and last-mile transport of parcels. Therefore, this section is justified by the finding in Section 4.1 and aims to answer RQ3 by introducing a novel MAS. As proposed by Heinbach et al. (2022*b*), one objective of the MAS is to increase the automation in the order management of parcel deliveries. As a second objective, the MAS should include state-of-the-art technologies like delivery robots for the first- and last-mile deliveries and telematic-equipped trailers and swap bodies for the long-haul transport of parcels. The third objective is to realize horizontal and secure data flows between the software agents of the MAS and the distributed vehicles and other resources. Based on these three main objectives, the functions of different actors and entities along the transport chain for parcel deliveries were defined and assigned to different types of software agents (see Figure 3). More exactly, the desired MAS should cover the following software agents and functions to realize the objectives of a more automated management of systems for parcel deliveries that include delivery robots and telematic-

equipped trailers and swap bodies: Firstly, a delivery agent (1) is needed representing a parcel delivery robot responsible for bidding for first- and last-mile transport orders, for optimizing the robot’s tour, for sending driving commands to the robot, and for the management of customer interactions. Such a delivery agent could belong to a parcel delivery service company. A trailer agent (2), representing a physical swap-body or a trailer, should manage the long-haul transport, including the bidding for freight lists, tour optimization, and the insertion of workshop visits. The trailer agent could be hosted by a transport service company. As the handling of freight between the different types of vehicles takes place at depot facilities, a depot agent (3) is necessary. This agent should receive the estimated time of arrival (ETA) of delivery agents (1) and trailer agents (2) at depot facilities to coordinate appropriate docking procedures. Depot agents might run in the realm of freight forwarding companies. Further, an entity has to manage the connection between an external booking platform, which can be used by customers to create bookings for parcel deliveries, and the delivery agents and trailer agents. Thus, the booking agent (4) is defined that interfaces with the booking platform and divides shipping orders into freight orders (i.e., long-haul transport between depots) as well as transport orders for first- and last-mile (i.e., parcel pickups and deliveries). For instance, a booking agent could represent a shipper. Another function of the booking agent is to update the customers of a shipper about the current status of their parcel deliveries. Since each long-haul transport between two depots includes a multitude of parcels, a bordero agent (5) is necessary to combine freight orders into consolidated loading lists (so-called “borderos” (Oelfke 2005)). Bordero agents could belong to freight forwarding companies. Lastly, workshop facilities were identified as a relevant actor in the transport network, resulting in the workshop agent (6), responsible for handling maintenance orders initiated by trailer agents (2). Workshop agents might represent individual workshop companies and can bid for maintenance orders and optimize their schedules after winning an auction. Figure 3 illustrates a top-level conceptual framework of the MAS proposed in the consortium research project Gaia-X 4 ROMS.

The software agents are planned to be operational on a physically distributed system, thereby realizing the concept of decentralized fleet management. The third objective of the MAS – but also of the Gaia-X 4 ROMS consortium research project in general – is to have secure and horizontal data flows within the distributed system. To this end, we will follow the Gaia-X standards to create a federated and self-sovereign data ecosystem (Otto & Burmann 2021, Konietzko et al. 2022).

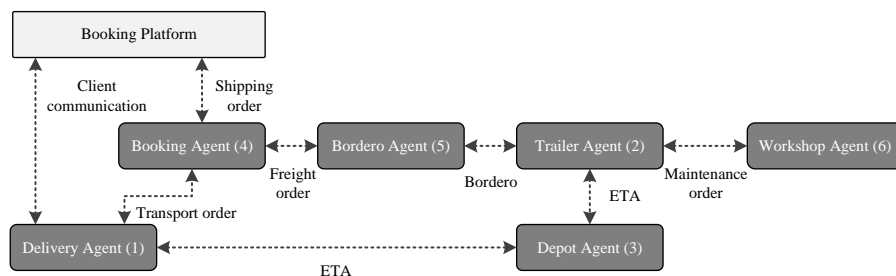


Figure 3. Concept of the MAS comprising six different types of agents as well as an auxiliary booking platform.

5 Discussion

Through a systematic review of existing literature, this study aims at providing a comprehensive understanding of the research concerning the application of MAS for intermodal freight fleet management (RQ1). This supports a deeper understanding and contextualization of the project within the research landscape. The results presented in Section 4.1 indicate a sustained level of interest in the topic in academia, while a notable research deficit in the current literature pertaining to the utilization of MASs in the logistics industry, especially parcel delivery, was identified. Subsequently, RQ2 was addressed by the observation that only in a limited number of studies (Dorer & Calisti 2005 a,b , van der Putten et al. 2006, Robu et al. 2008), the presented MASs for managing freight fleets reached or approached the stage of deployment. Moreover, none of the solutions regard the entire intermodal transport chain. Further, all of the studies deviated in the core concepts from the one of the consortium research project, either by focusing on centralized deployment or incorporating agents not representing transport entities. This finding is corroborated by the related literature reviews, that were identified and presented in the introduction of this work (Section 1).

During the systematic literature analysis, various factors influencing the validity of this study were identified. First, during the screening process it became apparent that many studies do not strictly distinguish between the concepts of MASs and agent-based simulation or use these terms interchangeably. However, this issue predominantly occurred during the full-text assessments, suggesting that the exclusion process in previous steps was lenient enough to tolerate concepts of agent-based simulation (type-I error). This also implies a low rate of inadvertent exclusion of MASs (type-II error), satisfying the requirement of a comprehensive review. Further, as outlined in Section 4.1, not all studies identified in the initial retrieval could be accessed, potentially introducing an unknown degree of publication bias that could not be addressed. Finally, the data retrieval and screening was conducted by a single researcher, increasing the likelihood of selection bias (Dyba et al. 2005). However, a rigorous research protocol was established beforehand (Section 3.2) to ensure objectivity and reproducibility of the selection process. Regarding the data abstraction outlined in Section 4.1, concepts were derived from examining the consortium research project and identified in the primary studies. Nonetheless, it was not always evident whether a study addressed a specific concept. For instance, the distributability of a MAS concept was frequently implied by the mention of decentralized agent communication. Furthermore, as some studies covered abstract concepts of various logistics problems, it was not always clear how they were allocated to specific segments of the transport chain. One example in this context is the work of Elfazziki et al. (2009) in which an agent-based concept for general road transport is proposed with the focus on the negotiation and task-planning aspects.

Justified by the findings of the literature review, that revealed the lack of applied solutions for relevant MASs, Section 4.2 introduced a novel concept for a MAS, which was developed and evaluated within the consortium research project. The concept serves as an answer to RQ3 and represents a comprehensive approach to managing an intermodal freight fleet with a MAS. The derived concept features six agent types representing the intermodal fleet (trailer equipment and parcel delivery robots), logistics facilities (depots

and workshops), and order processing aspects (bookings and borders). The approach enables the holistic agent-based management of a freight fleet dedicated to parcel delivery.

6 Conclusions and Future Work

This work represents the fundamental research of the Gaia-X 4 ROMS project, a consortium research endeavor focusing on developing a MAS for an integrated management of intermodal freight fleets in order to increase the automation of parcel logistics and thereby cope with the increasing number of parcels deliveries. After conducting a thorough analysis of existing literature reviews, it can be inferred that the utilization of MASs in the field of logistics remains limited and the identified literature reviews do not cover the precise concepts of the MAS as envisaged by the consortium research project. This necessitated a systematic literature review confirming a lack of applied multi-agent-based approaches for the integrated management of intermodal transport chains. Hence, this work justifies the innovative MAS concept for intermodal freight fleet management, consisting of software agents for parcel delivery robots, trailers, depots, booking activities, consolidation activities, and workshops.

Additionally, the consortium research approach encourages continuous collaboration with practitioners, guaranteeing a high degree of applicability of our proposed solution in real-world logistics scenarios. The integration of the consortium research project into the Gaia-X project ensures adherence to state-of-the-art concepts of data security and sovereignty, making it designed for long-term and sustainable use. Given the ongoing expansion of the parcel delivery market and the rise of new technologies like IoT devices, it is reasonable to anticipate that innovative strategies, such as the proposed MAS concept presented in this study, will attain increased relevance in forthcoming years.

As outlined at the outset, this study serves as a foundation for the first steps in the consortium research project and highlights the necessity of a novel agent-based approach. Accordingly, detailed design principles for each type of software agent based on the work of Gregor et al. (2020) and Wahlster (2017) are being developed and will be presented in future work. Moreover, the agents' routines for self-regulation as well as the agents' optimization models, data models, learning models, and their interactions with stakeholders will be defined. Further on, the evaluations of the agents' design principles and of the agents' detailed technical concepts are being conducted to achieve a solid technical ground for prototyping along the phases of the DSRP.

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