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# A Critical Review of the Use of Holonic Paradigm in Traffic and Transportation Systems

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## Abstract

The paper presents a critical review of the use of holonic paradigm in order to model and simulate traffic and transportation systems. After an introduction presenting the principles of this paradigm as well as its frameworks and concepts, the paper surveys existing works using the holonic paradigm for traffic and transportation applications. This is followed by a detailed analysis of the results of the survey. In particular, the relevance, the design approaches and the holonification orientation methodologies are investigated. Finally, based on this extensive review, open issues of holonic paradigm in modeling and simulation of traffic and transportation models are highlighted.

*Keywords:* Holonic Multi-Agent System; Holonic Manufacturing System; Multilevel; Traffic; Transportation.

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## 1. Introduction

The increasing demand for mobility in the 21<sup>st</sup> century and the limited capacity of the aging infrastructure cause several economic, financial and environmental problems related to traffic and transportation in several countries.

5 For example, in the environmental domain, vehicles produce greenhouse gases and pollutants. Moreover, the economic consequences of fuel consumption and time lost in traffic jams are considerable. For instance, in 2007, in the European Union (EU), the cost of congestion was estimated at €100 billions [33]. Added

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to this, incidents and accidents are caused by the deterioration of traffic conditions. Considerable efforts and resources have been invested all over the world to overcome those shortcomings. Although, we are witnessing some sporadic improvements in detail, the overall situation has not only changed a little but is still deteriorating with the ever-increasing traffic congestion [92]. Modeling and simulation of traffic and transportation have been underlined as one of the interesting means to improve the conditions of movement of goods and people [77]. Several methodologies have been proposed in literature to model and simulate traffic and transportation such as the agent-based paradigm [112], differential equations [57], partial differential equations [26], and the holonic paradigm [88] to name a few. The latter allows to represent a system from several angles through the concept of a holon. The term “holon” was originally coined by Arthur Koestler based on the Greek word “holos” for “whole” and the suffix “-on” that denotes “part”. According to Koestler, a holon is a fractal structure that is stable, coherent, and consisting of several holons acting as substructures. To explain the holon concept, Koestler provides an example from biology: a human being consists of organs which in turn consist of cells that can be further decomposed and so on; none of these components can be understood without its sub-components or without the super-component it is part of [38]. One of the strengths of holonic paradigm is that it enables the construction of complex systems exhibiting hierarchical behavior, highly resilient to disturbance, and adaptable to changes in the environment [13].

The first works using holonic paradigm to model traffic or transportation were proposed around the year 1998 [53, 18]. Thereafter, in the same vein, several other works have been proposed. After around twenty years of the use of holonic paradigm for traffic and transportation systems, an evaluation of the relevance of this technology related to traffic and transportation seems useful. To this end, the contribution of this paper is twofold: *(i)* it surveys the state-of-the-art of traffic and transportation models using holonic paradigm and, *(ii)* it provides an assessment of the use of the holonic paradigm in traffic and transportation systems. To address the second goal of the paper, five Research

40 Questions (RQ) were adopted:

- **RQ1:** What are the benefits of the holonic paradigm in traffic and transportation?
- **RQ2:** What are the drawbacks of the holonic paradigm in traffic and transportation?
- 45 • **RQ3:** How to design traffic and transportation models using the holonic paradigm?
- **RQ4:** What are the holonification design orientations of traffic and transportation models?
- **RQ5:** What are the open issues of the use of holonic paradigm in traffic  
50 and transportation? And, what are the general insights toward a solution?

Seeking to address these research questions, the rest of the paper is organized as follows: Section 2 presents the research motivations and methodology of the paper. In Section 3, a brief description of the holonic paradigm, principles and concepts is presented. Section 4 summarizes the research works of  
55 the use of holonic paradigm for transportation within a manufacturing system. Section 5 summarizes the research works on modeling and simulation of traffic and transportation using holonic paradigm. Section 6 identifies the motivations, drawbacks and open issues of the use holonic approach in traffic and transportation. Finally, Section 7 gives the conclusion and points out the future works.

## 60 **2. Research Motivations and Methodology**

This section firstly presents related works and motivation of the paper, then it presents the research methodology and the scope of the paper.

### *2.1. Related Works and Motivation*

There are several survey papers and books dedicated to traffic and transportation in the literature. Brackstone and McDonald [15] proposed an overview  
65

of the available car-following models in literature. Typically, these models describe the processes by which drivers follow each other in a traffic stream. Generally, car-following models involve many parameters that must be calibrated before the model can be used as a prediction tool. Hollander and Liu [55] provided a review of around twenty different calibration methodologies whose goal to guide traffic analysts through the basic requirements of the calibration of microscopic simulation models.

Regarding macroscopic models, Daganzo [26] described the logical flaws in the arguments advanced to derive several macroscopic models (higher order continuum models), and showed that the proposed high order modifications lead to a fundamentally flawed model structure. Based on this work, many of existing macroscopic models have been re-considered Mohan and Ramadurai [75]. In the same vein, Gartner et al. [44] focused their survey on traffic flow while Jaume [57] focused on tools for traffic and transportation simulation.

Another interesting approach to deal with traffic and transportation is agent-based modeling [112, 97, 29, 69, 56, 39]. This works starts from the following premise: the distributed nature of traffic and transportation processes, and the strong independence among entities involved in such processes, make agent-based modeling a key solution for the engineering of effective, real-world applications for both traffic management and transportation logistics [27].

Several surveys were conducted to understand, analyze and compare existing works using agent-based modeling for traffic and transportation. For instance, Davidsson et al. [27] surveys agent-based technologies mainly adopting a logistical perspective and focusing on freight transportation, while Chen and Cheng [20] examines agent-based approaches and their applications in different transportation modes, including roadway, railway, and air transportation. Bazzan and Klügl [11] reviews the literature related to the areas of agent-based traffic modeling and simulation, and agent-based traffic control and management. Mualla et al. [79, 78] provides a systematic literature review and research directions on agent-based modelling and simulation for aerial transportation using Unmanned Aerial Vehicles. Ronald et al. [90] reviews individual and

agent-based approaches modeling demand-responsive transportation systems. Demand-response is a transit mode involving passenger cars, vans or small busses operating in response to calls from passengers or their agents to the transit operator, who then dispatches a vehicle to pick up the passengers and transport them to their destinations.

As presented previously, most of the review papers focus on the use of agent-based paradigm, partial differential equations, differential equations, and fuzzy logic to model traffic and transportation. A survey reviewing the use of the holonic paradigm is still missing from in the literature. To address this lack, we provided in one of our previous work a brief review of holonic paradigm in traffic and transportation [99]. However, this work was an initial step that didn't enough details to identify, compare and analyze existing works using the holonic paradigm. Therefore, this current paper extends very largely our previous work and provides a comprehensive survey of the use of holonic paradigm to model traffic and transportation systems.

## 2.2. Research Focus and Methodology

Davidsson et al. [27] provided definitions of both traffic and transportation, and we focus on their work to define these concepts. Transportation is defined as an activity where someone or something moves from point  $A$  to point  $B$  by one or several modes of transportation (air, water, and ground transportation which includes rail, road and off-road transport). The research domains that fall under the transportation category are: route planning, fleet management, different sorts of scheduling and rescheduling, etc. Traffic refers to the flow of different transportation within a network. We can cite among others, road traffic, pedestrian traffic, railway traffic. Some traffic systems exhibit a hierarchical behavior like road traffic [98] and pedestrian traffic [46] and therefore three main granularity levels are presented in the literature:

- Microscopic models describe the entities of the system as well as their interactions at a high level of detail. Microscopic modeling of traffic flow is based on the description of the movement of each entity composing

the flow. These models tend to be most close of the real behavior of the entities.

- Mesoscopic models. These are an intermediary representation between the macroscopic and the microscopic level. Entities are no longer considered individually but they are grouped according to close and homogeneous traffic characteristics.
- Macroscopic models characterize the global behavior of traffic. They have been used to understand and predict the formation of congestion and its propagation on the network.

The Holonic paradigm allows to represent a system at several abstraction levels [58, 54], and therefore can capture the hierarchical behavior exhibited by traffic. In this paper, as stated before we aim to give a comprehensive overview of the use of holonic paradigm in the modeling and simulation of traffic and transportation systems. To this end, we start our work by systematically searching for articles in literature in Scopus, Web of Science and IEEE Xplore databases with the following keywords: “holonic traffic”, “holonic transport”, “holonic transportation”, “holon traffic”, “holon transport”, “holon transportation”, “multilevel traffic”, “multilevel transport”, “multilevel transportation”, “hierarchical traffic”, “hierarchical transport”, “hierarchical transportation”.

We double checked the literature by using the same keywords in the Google Scholar database as presented by Figure 1. Papers focusing on either traffic or/and transportation using holonic paradigm were retained. After reading the abstracts of the papers and skimming them, we observed that two main different holonic paradigms were used to model traffic and transportation: Holonic Multi-Agent System and Holonic Manufacturing System (more details are provided at Section 3).

Therefore, more specifically, the paper focuses on:

- **Holonic Paradigm:** The holonic paradigm considered in this paper is Holonic Multi-Agent System (HMAS) and Holonic Manufacturing System

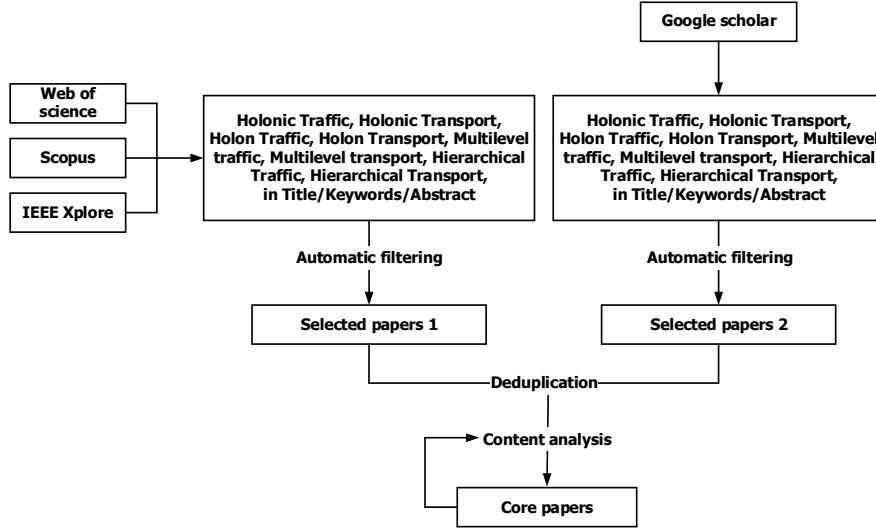


Figure 1: Procedure of literature search inspired by [113]

(HMS).

- **Traffic and Transportation:** We have chosen not to restrict ourselves to road traffic nor road transportation. In fact, our goal is to have a wide vision of the use of holonic paradigm in traffic and transportation. Therefore, most of the works using either HMAS or HMS to model traffic and transportation systems found in literature were considered, even transportation systems within a manufacturing system. Although transportation in manufacturing systems has different features than road transportation, the former deals with the management or scheduling the movement of goods from point  $A$  to point  $B$  [64] (i.e. the definition in Davidsson et al. [27] still roughly applies). For this reason, we chose to consider it in this paper. In addition, the management of the devices used for transportation in manufacturing systems, are not exclusive to manufacturing systems. For example, straight escalator, straight conveyors are used in airport for moving goods and pedestrians and therefore fo-



cusing on the transportation aspect in manufacturing systems i.e the way transportation devices are managed or scheduled inside a manufacturing systems can be reused in other domains than manufacturing systems.

### 3. What is Holonic Paradigm?

175 Holonic paradigm is a suitable approach to reduce the complexity of complex systems by defining several abstraction levels [89, 46]. Holonic paradigm is used to model the intrinsic hierarchical nature of systems. The holonic concept was developed by the Hungarian philosopher Koestler to explain the evolution of biological and social systems. As stated before, the biological example which  
180 explains the holonic thinking presents the recursive decomposition of humans in organs, cells etc. [58]. This example shows the interdependence between the sub-components and the super-components of a human and the idea of holonic thinking. The idea highlighted by the holonic concept is that all the properties of a given system cannot be determined or explained by their component parts  
185 alone. Aristotle described the general principle of holism by: “the totality is not, as it were, a mere heap, but the whole is something besides the parts” [4]. This original description is usually summarized as: “The whole is more than the sum of its parts” [45, 89, 48, 95, 58]. A holon, according to Arthur Koestler is defined as simultaneously a whole and a part of the whole, thus it can be made up of  
190 other holons, strictly meeting three conditions: being stable, having a capacity for autonomy and being able to cooperate. In other words, the term holon indicates any object or concept observable on three levels: (i) as an autonomous and independent unit that acts according to its own behavioral “canons”; (ii) as a superordinate unit, possessing emerging properties, with respect to the component parts that it transcends; and (iii) as a subordinate unit in that it  
195 is part of a vaster whole that conditions it [58, 71]. The definition of holons of Koestler [58] is general and depending on the domains, this definition can be specified. One of the most interesting properties of the holonic systems, and the essence of their complexity, is that a holon can be both an entity and an

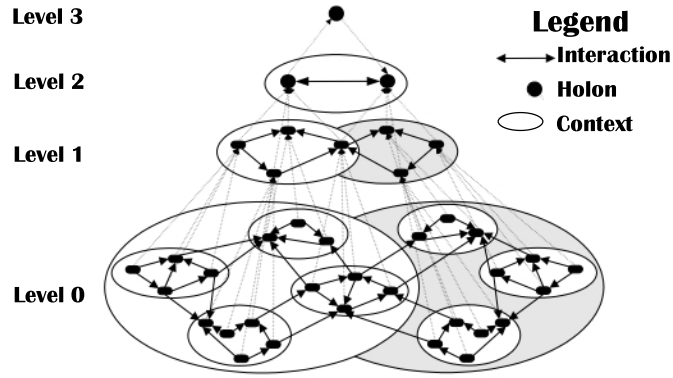


Figure 2: An example of a holarchy [45]

organization [46]. This duality is generally called the Janus<sup>1</sup> effect. The holons are therefore stable and self-similar structures connected within a holarchy.

Koestler [58] defined a holarchy as a hierarchy of self-regulating holons which function (i) as autonomous wholes in supra-ordination to their parts, (ii) as dependent parts in sub-ordination to control higher levels, (iii) in co-ordination with their local environment. In the same vein, holonification is the process of building a holarchy. Figure 2 presents an example of a holarchy with four holarchical levels. As shown on Figure 2, a holarchy allows two types of communications [88]: (i) intra-level communication: holons communicating with holons at the same level ("horizontal communication"), and (ii) inter-level communication: when holons of two different levels communicate ("vertical communication").

After presenting the main concepts of holonic paradigm, we present also the fields of application of this technology. Holonic paradigm has been successfully applied in several domains in scientific community such as philosophy [110], health [104], robotic football team [8], collaborative work [3], traffic and transportation etc. In the latter, two main holonic paradigms were used those are

<sup>1</sup>Janus is an ancient Roman god depicted as having two faces, since he looks to the future and to the past.

HMAS and HMS. In the following we present both of them.

### 3.1. Holonic Multi-Agent Systems

HMAS is based on the concept of holonic paradigm, developed by Koestler  
[58]. The underlying idea of HMAS is that several holons can be grouped (resp.  
splitted) to form other higher-level holons (resp. lower-level holons), generating  
thus a hierarchical system. HMAS can be seen as a recursive structure of holons  
[48]. The reference definition of holons that follows the global idea of the defini-  
tion of Koestler [58] in the domain of HMAS is embodied in the introduction of  
HMAS done by Gerber et al. [48] where a vision of holons is proposed that cor-  
responds more to the notion of a recursive or a composed agent (an autonomous  
and flexible entity that can perceive its environment by sensors and act on it  
by actuators). In other words, a holon in HMAS is “an agent that could be  
composed of other agents” or “an agent consisting of other agents” [48, 46].

#### 3.1.1. HMAS Organization

To structure a community of holons within HMAS, Fischer et al. [38] iden-  
tifies three main possibilities presented in Figure 3, those are:

- **Federation:** full sub-holons autonomy. Super-holon is a set of au-  
tonomous sub-holons presented in Figure 3a. Super-holon is realized ex-  
clusively through cooperation among the sub-holons.
- **Fusion:** no sub-holons autonomy. Several sub-holons merge into super-  
holon presented in Figure 3b. A super-holon is the union of the sub-holons  
with capabilities that subsume the functionalities of the sub-holons. The  
merging holons completely forsake their autonomy but they may be re-  
invoked when the super-holon is terminated. Realization of this approach  
assumes procedures for splitting and merging holons that lead to the cre-  
ation of a new holon.
- **Moderated group:** intermediate sub-holons autonomy. This approach  
presented in Figure 3c considers a hybrid way of forming a super-holon,

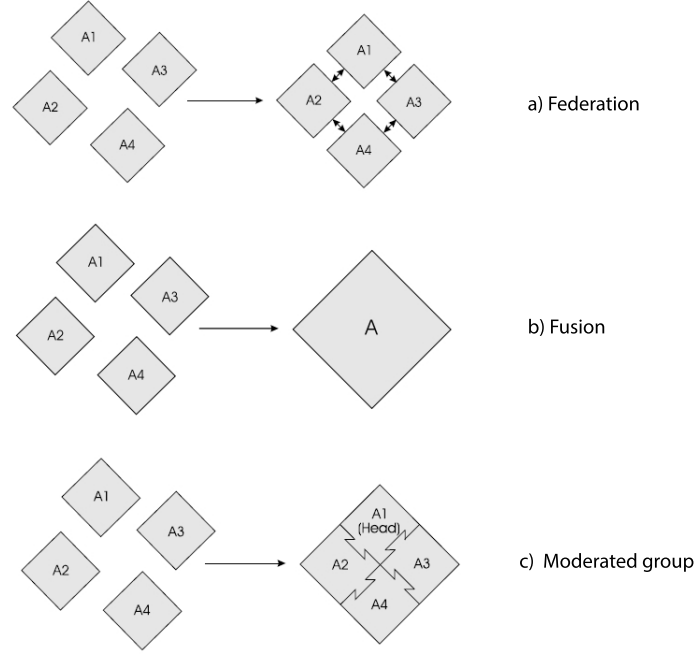


Figure 3: Holonic observation [38]

245 where sub-holons give up only part of their autonomy to the super-holon.  
 This approach brings out the head holon which represents the super-holon  
 outside to the rest of population. The head competence may range from  
 purely administrative tasks to the authority to give directives to other sub-  
 holons. Moreover, the head may have the authority to plan and negotiate  
 250 for the super-holon, and even to remove some sub-holons or to incorporate  
 new sub-holons.

### 3.1.2. Frameworks for designing systems by HMAS

Several frameworks, metamodel have been proposed in literature to design  
 systems by HMAS. In the following, we present some of them which have been  
 255 used to model traffic and transportation applications.

The CRIO (Capacity - Role - Interaction - Organization) metamodel [86,  
 22] is a general framework for designing HMAS. CRIO is based on four main

interrelated concepts:

- **Capacity** is a description of a know-how/service. This description contains at least a name identifying the capacity and the set of its input and output variables which may have default values.
- **Role** is the abstraction of a behavior in a certain context and confers a status within the organization. Roles may interact with other roles defined in the same organization.
- An **Interaction** links two roles in a way that an action in the first role produces a reaction in the second.
- The **Organization** concept combines roles and their interactions. A set of roles and their interactions pattern define an organization in a specific domain.

CRIO metamodel aims at providing a full set of abstractions to model HMAS under an organizational perspective. CRIO uses the development approach defined in Model Driven Architecture (MDA) [81]. The concepts of CRIO are organized in three domains: (i) The Problem Domain (CIM – Computation Independent Model) deals with the user’s problem in terms of requirements, organizations, roles and ontologies; (ii) The Agency Domain (PIM – Platform Independent Model) addresses the holonic solution to the problem described in the previous domain; (iii) Finally, the Solution Domain (PSM – Platform Specific Model) describes the structure of the code solution in the chosen implementation platform. CRIO is used by Gaud et al. [46] and Rodriguez et al. [88] to design their traffic models. CRIO metamodel has been extended to model human activities, named K-CRIO [65]. K-CRIO uses a semantic layer for collaborative software to enhance knowledge management within the targeted organizations. CRIO has also been extended to consider the norms named NCRIO [72].

ASPECS [23] is an agent-oriented software process for complex engineering systems. ASPECS allows the development of a HMAS. ASPECS is based

on a holonic organizational metamodel and provides a step-by-step guide from requirements to code allowing the modeling of a system at different levels of detail using a set of refinement methods. ASPECS integrates design models  
290 and philosophies from both object-oriented and agent-oriented software engineering. The process described by ASPECS was followed by Galland and Gaud [40], Galland et al. [41] in their environment traffic model.

SARL [85, 96] is a general statically-typed agent-programming language with emphasis on holonic agents. SARL aims at providing the fundamental  
295 abstractions for dealing with concurrency, distribution, interaction, decentralization, reactivity, autonomy and dynamic reconfiguration. SARL can be used for agent-based simulations because SARL provides features for agent execution and direct communication. The particularity of SARL language is that, agents are holons. SARL provides therefore a complete support for holons allowing  
300 the development of HMAS. SARL is generally coupled with Janus [42] as an execution platform. Tchappi et al. [100] use the SARL programming language in their road traffic implementation model.

### *3.2. Holonic Manufacturing Systems*

#### *3.2.1. Basic Definitions*

305 HMS was proposed as a new manufacturing paradigm and received a lot of attention in both academic and industrial research. HMS aim at meeting the challenges of manufacturing environments for mass customization or low-volume and high-variety products. The underlying idea of HMS is to provide a dynamic and decentralized manufacturing process, in which humans are effectively inte-  
310 grated, so that changes can be made dynamically and continuously. In other words, HMS is a paradigm for next-generation manufacturing systems, which presents a concept that can be used to achieve agile manufacturing systems [17]. HMS is based on the holonic paradigm developed by Koestler [58].

Following the global definition of holons done by Koestler [58], a holon in  
315 HMS is an autonomous and co-operative building block of a manufacturing system for transforming, transporting, storing and/or validating information

and physical objects. Holons in HMS assist the operator in controlling the system: holons autonomously select appropriate parameter settings, find their own strategies and build their own structure. Holons in HMS consist of an information processing part and sometimes a physical part. A holon can be part of another holon.

### 3.2.2. Frameworks for HMS design

Several frameworks have been proposed in literature to design systems by HMS. In the following, we present some of them which have been used to design traffic and transportation applications.

PROSA (Product-Resource-Order-Staff Architecture) [17] is a reference architecture for holonic manufacturing systems design. PROSA appeared in 1995 and since that date, it has attracted many researchers and industrial pioneers. Valckenaers [105] outlines the different steps of the history of PROSA. PROSA is composed by three basic holons (Product holon, Resource holon, and Order holon) and by another holon named Staff holon dedicated to assist the basic holons with expert knowledge. The basic holons are responsible for decision making while staff holon stands as an external expert that gives advises to basic holons such that when staff holons are added, the basic holons tend to follow this advice as much as possible. Resource holon is an abstraction of the production means and may represents a factory, a shop, machines, conveyors, tools, pipelines, pallets, furnaces, components, raw materials, tool holders, material storage, personnel, energy, floor space, etc. A product holon holds the process and product knowledge to assure the quality of the product. A product holon contains consistent and up-to-date information on the product life cycle, user requirements, design, process plans, bill of materials, quality assurance procedures, etc. Finally, an order holon represents a task in the manufacturing system. Order holon is responsible for performing the assigned work correctly and on time. The basic holons are structured using object-oriented concepts like aggregation (a set of related holons are clustered together to form a bigger holon with its own identity) and specialization (separation of holons with re-

spect to their characteristics). PROSA reference architecture is used by Roulet-Dubonnet et al. [91], Liu et al. [68], Philips et al. [83] in traffic and transportation application. Nowadays, the PROSA architecture has been refined and retitled  
350 into the Activity Resource Type Instance (ARTI) architecture. The reader can refer to [106, 105] for more information about ARTI and PROSA.

Babiceanu et al. [6], Babiceanu [7] outline a dedicated framework for the control of automated material-handling systems using the holonic approach in a manufacturing system. The proposed holonic control architecture is formed  
355 by five types of entities: order holons, three types of resource holons (machine, material handling and equipment), and another entity called a global scheduler that holds a general image of the entire system. This framework is used by Roulet-Dubonnet et al. [91] in the motion of automated material-handling.

### 3.2.3. Others Frameworks to Design Traffic and Transportation System by Holonic 360 Paradigm

Muller and Pischel [80], Fischer and Kuhn [36] propose INTERRAP, an architecture for the dynamically interacting agents. INTERRAP has been developed to cope with the basic requirements for cooperative intelligent systems i.e. to meet the requirements of modeling dynamic agent societies. INTERRAP  
365 provides means to combine reactive behavior of agents with explicit planning facilities. INTERRAP architecture is used by the work of Bürckert et al. [19] in fleet management.

Davis and Smith [28] propose a framework called Contract Net Protocol (CNP) that specifies communication and control in a distributed problem solver.  
370 The aim of this framework is to manage task distribution. CNP supplies a mechanism to solve the connection problem. Nodes with tasks to be executed negotiate with idle nodes over the appropriate matching of tasks and nodes. The framework does not require neither global data storage nor global control and allows some degree of dynamic configuration and reconfiguration making  
375 the CNP more appropriate to deal with a distributed problem solver. Sandholm [93] extends CNP by an implementation of CNP based on marginal cost



calculations. CNP is also extended by Fischer et al. [37] into what they called Extended Contract Net Protocol (ECNP) by the decentralized task decomposition to overcome the knapsack problem generated by the pure CNP. CNP is used by Hans-Jürgen et al. [54, 53], Liu et al. [67, 68], Gołacki et al. [51] in their traffic and transportation models.

### 3.3. HMAS vs HMS

In the same vein, although both HMAS and HMS focus on holism thinking view, there are several differences between these paradigms. Table 1 presents some similar and dissimilar HMAS and HMS features.

Properties	HMAS	HMS
Thinking view	Holism	Holism
Main component	Holon (agent composed by agents)	Holon (manufacturing system building block)
Emergence	Arise trough holonification (grouping agents)	Arise through holons decision making
Scope	Wide	Limited (usually inside manufacturing)
Recursion modeling	Fundamental	Generally not important
Government	Assumption about head in moderated group	Generally no assumption about head
Entities interconnected scheme	Dynamic	Generally predefined a priori
Deph of the holarchy	Variable	Generally Fixed
Scaling	Yes	Yes

Table 1: Main differences between HMAS and HMS

### 3.4. Holons vs Agents

Holons and agents have some conceptual similar properties. In fact, both holons and agents have properties like autonomy, social ability, mobility, learn-

ing to name a few. Therefore, one recurring question arises when talking about holons and agents that is: what is the difference between holons and agents? Or how are holons linked to agents? To address this question, and to avoid confusion between holons and agents, Giret and Botti [49] have proposed a general comparison between holons and agents. Inspired by this work, we provide in Table 2, some similarities and dissimilarities properties of holons and agents.

Properties	Agents	Holons	Property explanation
Composition	Usually atomic	Composed	Highlight if the entity consists or not of sub-parts
Autonomy	Yes	Yes	The entity can operate without the direct intervention of humans or other entities
Reactivity	Yes	Yes	the entity reacts to the environment it is in
Pro-activity	Yes	Yes	The entity can try to fulfill it's own plan or goals
Social ability	Yes	Yes	The entity can communicate with other entities
Cooperation	Yes	Yes	The entities work together towards a common aim
Learning	Yes	Yes	The entity can adapt to changing environment
Benevolence	Yes	yes	The entities cooperate whenever and wherever possible
Rationality	Yes	Yes	The entity tries to compute an optimal solution
Virtual entity	Yes	Yes	Modeling a software entity
Physical entity	Yes	Yes	Modeling a physical entity
Recursiveness	Usually no recursive architecture	Yes	Containing/content observation

Table 2: Main differences between Agents and Holons inspired from [49, 109]

#### 4. Literature Summaries of The Use of Holonic Paradigm for Transportation Within a Manufacturing System

Production, storage, transportation etc. are among others some key points of the manufacturing process. According to the scope of the paper, we focus only on transportation. Most of works focusing on transportation within a

manufacturing system is related to material handling. In fact, although material handling system is considered as a process without added value to the finished product, it can constitute a substantial portion of the whole production time, use significant factory space and thereby add considerably to the finished product cost. So, an efficient material-handling system is therefore essential for every manufacturing system.

The model of Liu et al. [67, 68] is among the first models using a holonic paradigm for material handling management. The authors were inspired by HMS to develop a decentralized architecture for the coordinated control of AGVs (Automated Guided Vehicles). AGVs are ground robots, usually used for transportation goals on the manufacturing shop-floor. The model proposed is based on PROSA with some modifications. In this model, the resource holon is the physical AGV (motor, batteries, steering system, and other hardware) and its control system. The product holon contains the knowledge of the capacity of the AGV, and the facility floor planning or path layout. The goals of the product holon is to search for efficient and effective paths, to generate a response for each transportation service request based on the AGV's current and future state. The order holon may represent a transportation task. The order holon specifies the departure and destination positions of the service request, the time need for the service, the material to be transported, and other information required by the AGVs to provide the service. The staff holon can perform different roles like the activities of the AGV system and provides global optimization advice to the basic holons. The authors propose a scheme representing interaction between holons. Cooperation among AGVs is made through CNP. The results of simulation demonstrated that a holonic AGV system can operate successfully in a shop floor environment. In fact, their results indicate that their proposed holonic AGV system improves both the performance of the overall manufacturing system, and also provides greater flexibility and robustness. However, the main drawback of this mechanism is that the proposed AGV system cannot provide accurate prediction.

Roulet-Dubonnet et al. [91] presented a dynamic management of AGVs sys-

tem under development and its industrial background. The proposed model is also based on PROSA. Here, resource holons are physical devices (AGVs or groups of AGVs) and product holons are part to manufacture (containers for information about the parts to transport). Order holons are generated for each transportation request (driving force of the holonic system) and staff holons are adviser. The main drawback of this work is that there is no experimentation nor simulation of the proposed holonic AGV and therefore no validation is provided by authors, just three use cases are provided. Lind and Roulet-Dubonnet [66] extended this model. Nevertheless, even in this extension the model was still under development and no implementation was given by authors to validate their proposal.

Kruger and Basson [60] aimed at outlining the relevance of Erlang programming language in holonic control implementation. Erlang is a functional programming language developed for programming large-scale, distributed control applications and freely available [5]. The main benefits of Erlang are strong scalability, concurrency and fault-tolerance. The use case related to transportation of the paper is the control of a modular conveyor system. The conveyor implementation is based on PROSA as a resource holon. The conveyor holon is responsible for the movement of carriers (which transport products or work pieces around the cell) by controlling the actions of the conveyor hardware. This model has been updated by Kruger and Basson [61]. Moreover, in comparison with JADE, Erlang is especially very well suited for implementing holonic control, offering several important benefits, and warrants further exploration and development [62]. Also based on HMS, Van Belle et al. [107] proposed an approach for the control of a chain conveyor for product flow management and Trentesaux and Branger [102] survey holonic and not holonic fleet of complex transportation system.

## 5. Literature Summaries of The Use of Holonic Paradigm for Traffic and Transportation Applications

Since the interest of the paper is the study of holonic paradigm for traffic and transportation application, the papers presented in this section focus on holonification and on the organization of the structure of holarchy.

### 5.1. Mobility of individuals

Gaud et al. [47, 46], Gaud [45] proposed a holonic organizational multilevel model for real-time simulation of pedestrians by exploiting the hierarchical and distributed properties of the holarchies. In this model, each pedestrian is associated with an atomic holon. These atomic holons are grouped into super-holons according to their affinities. Then super-holons are grouped in their turn, and so on, to obtain a single and complete holarchy. The pedestrian behavior of a super-holon is the same of its sub-holons but perceptions/actions are aggregated. The holons formation is therefore bottom up, and it is strongly related to a force-based model that is used as the agent's motion behaviors. The authors estimated the deviation of simulation accuracy between two adjacent levels through physics-based indicators. These indicators allow to dynamically determine the most suitable level for each entity in application to maintain the best compromise between simulation accuracy and available resources. To evaluate the accuracy of their model, kinetic, goal-potential and constraint-potential energies were proposed. In experimentation, the authors implemented a 3D realistic model and simulation of pedestrians' motion. The authors validated their model saying that scheduling holarchy implies a reduction of computational cost. The main drawback of this method is the lack of generality because the proposal is designed for the force-based model only. Moreover, the authors showed the evolution of the energies of only three agents simulated at macroscopic level and one agent at the microscopic level which is a relatively small to be qualified as a large scale multilevel of pedestrian modeling and simulation.

Tchappi et al. [100] presented a holonification method based on graph theory to model large-scale road traffic. The paper presented three organizations based

on CRIO which represent road traffic flow: (i) Free Driver organization that  
490 define the role *Free* played by an agent, which is moving with its desired speed;  
(ii) Car Following organization that define the roles *Leader* and *Follower* such  
that the *Leader* is the vehicle located just in front of the *Follower*; (iii) Con-  
voy organization that define the roles *Head* and *Member* such that agent which  
495 plays the *Head* role is the vehicle on the top of convoy and the other agents  
vehicles which belongs to a convoy play the *Member* role. The holonifica-  
tion is made through graph theory such that vehicles are represented by the  
graph’s vertices and the follower→ leader relationship between vehicles by the  
graph’s edges. The main drawback of this work is that the holonification is  
made from a snapshot of road traffic with a very simplistic situation: snapshot  
500 of eleven vehicles located on one lane. The application of the model in real traffic  
situation is questionable. Moreover, in the graph bisection, authors do not con-  
sider the structural depth of the holarchy. Tchappi et al. [101] seek to improve  
the problem of structural depth by proposing a holonification model based on  
DBSCAN (Density-Based Spatial Clustering of Applications with Noise) [32].  
505 Although holarchy is well managed in this second model by a particular holon  
named cluster unit holon that is created to manage holarchy, the model keeps  
some drawbacks of its predecessor because holonification is also made from a  
snapshot of road traffic.

## 5.2. Fleet management

510 Hans-Jürgen et al. [54, 53] proposed TeleTruck to support dispatch officers  
in route planning, fleet management, and driver scheduling. TeleTruck is among  
the first HMAS model in transportation. TeleTruck uses HMAS to achieve a  
flexible, structured resource management in the planning process. In TeleTruck,  
the modeling of the physical components is made by agents i.e. equip them with  
515 plans, local goals, and the abilities to communicate, cooperate, and form holons  
in a multi-agent setting. Each driver is also represented by an agent. The  
agents collaborate closely and join together forming holonic agents that act in a  
corporated way. In the proposal, the Plan’n’Execute Units (PnEUs) are special

agents, which propose to coordinate the formation of the holons, and to plan  
520 the vehicles' routes, loading stops, and driving times. The authors proposed  
protocols and algorithm to deal with communication, coordination, and resource  
control of the holonic agents. The algorithm starts with an initial sub-optimal  
schedule and improves the solution through every negotiation cycle. According  
to authors, TeleTruck increases efficiency, transparency and leads to a reduction  
525 of traffic congestion, air pollution, and energy consumption. Gambardella et al.  
[43] extended TeleTruck model in the case of PLATFORM<sup>2</sup> project to combine  
rail/road transport.

Koźlak et al. [59] proposed a model for delivery strategy and management  
of a transportation of company. They introduced theoretical representation of  
530 the abstract holon structure and a model for building and reorganizing holons.  
The presented holonic system model was composed of three main modules: (i)  
Domain-independent holon organization which gives the formal definition of an  
agent-holon; (ii) Model for the transportation domain as a directed graph such  
that nodes represent locations and arcs represent roads; (iii) Dynamics and  
535 optimization techniques which ensure the most advantageous values of the goal  
function. The results presented by the authors showed that the quality of the  
proposed solutions are usually better than the higher number of the execution  
of the optimization algorithm. However, there were some random deviations in  
these results.

540 Gołacki et al. [51] proposed a holonic-based environment for management  
of a static and dynamic pool of transportation request in a company. There  
are several types of agents in the model: dispatcher agent (the manager), trans-  
portation unit agent (realizes transportation requests), truck agent, driver agent  
and trailer agent. Agents cooperate for the completion of transportation units  
545 and the minimization of costs of a given set of requests. Requests allocation be-  
tween agents is performed through CNP negotiations. Holons are created when  
a new request is received, if it enables a cheaper realization. During experi-

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<sup>2</sup><http://www.platform-project.eu/>

mentation, results showed that using smaller vehicles, it is possible to decrease costs. The results showed also the advantages of flexible planning using holonic paradigm.

Giuseppe et al. [50] presented a holonic remote monitoring for fleet management system. The goal of the authors is to propose a robust, flexible, responsive in real time model which consider the heterogeneous nature of vehicles. To this end, the authors proposed a holonic architecture composed of territory holon, central holon and web holon to represent the system. Territory holon in its turn is composed of sensor holon and actuator holon. Interaction among entities of the system is made through UML (Unified Modeling Language) and OWL (Web Ontology Language). The paper presented four uses cases to test the holarchy and interaction among holons at different system layers, and a demonstrator built by authors to validate the above use cases.

Versteegh et al. [108], Salido et al. [92] presented a holonic model for the global road transportation system. The authors proposed a definition and an algorithm to solve the challenges arisen by global automated transportation system. The system is composed by a network such that nodes are locations and arcs are roads. Nodes are points in the road or regions in a country depending on the level of detail. The duality of the holonic principle allowed the authors to observe the holons of system both as a whole and as a part. For example, a country can be observed as a whole (if the network is not increased and only optimal paths are calculated into the country) and as a part (if it is connected to other countries to calculate international paths). On the one hand, the proposed algorithm determines a high-level path in which a set of regions are selected to build up the holonic structure. On the other hand, the algorithm calculates the low-level path corresponding to the sup-optimal path. The worst case complexity of the proposed algorithm is  $O(N^2 R^2)$ , with  $R$  the number of regions in the system and  $N$  the number of nodes per region. In the same vein, Borangiu et al. [12] focused on public transportation. The goal of this model was to manage service planning and scheduling function. To this end, the authors proposed a holonic model composed by resource holon, route holon, order holon



and dispatcher holon.

#### 580 5.2.1. *Railway traffic*

Ciufudean and Filote [21] proposed an architecture for controlling and scheduling holonic distributed systems using Petri nets formalism and their properties. This architecture builds the holonic structure of railway traffic control. Railway is decomposed in three modules such that for each module a control structure is derived to ensure the traffic safety and fluency. The Petri nets is used to build a model of the detailed behavior of a railway system to optimize some pre-defined assigned performance criteria. Since railway system exhibits time related nature, the ordinary Petri net is insufficient to deal with the railway system and the authors therefore defined time-placed Petri net. The proposed time-placed Petri net contains three major modules that interact with each other: transportation planning, transportation control module and priority control module. The authors exemplified their architecture with three basic models for railway traffic control system. The proposed approach was implemented and tested in their laboratory and the results showed, according to the authors, that their approach is less time consuming and also safer, more reliable, and more versatile than the classic railway traffic control models.

Mortellec et al. [76] proposed an embedded holonic cooperative fault diagnosis approach to increase the embedded diagnosis capabilities of complex transportation systems. The method was applied to the fault diagnosis of door systems of a railway transportation system. Trains, vehicles and doors are the three holonic levels. The method was applied to a joint research-industry project named SURFER (SURveillance active FERroviaire) led by Bombardier-Transport<sup>3</sup>. To validate the model, the authors proposed three possible fault diagnosis scenarios in train passenger. These three scenarios illustrate the benefits of the approach of the authors compared to the others existing diagnosis

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<sup>3</sup>Bombardier Transportation is one of the world's largest companies in the rail vehicle and equipment manufacturing and servicing industry

architecture. Fadil et al. [34] extend the model of Mortellec et al. [76], willing to increase the level of availability of each entity while reducing the cost of a maintenance level fleet. Their results show that the proposed architecture increases on-board diagnostic capabilities and optimizes the overall maintenance  
610 of a fleet of mobile entities. Trentesaux and Branger [103] summarized the results of SURFER architecture regarding data management.

### 5.3. *Traffic environment*

Rodriguez et al. [88, 87] proposed a framework for the modeling and simulation of Peugeot car manufacturer at Sochaux, France. The goal of the proposal  
615 was to provide a set of tools to help the decision maker when preparing infrastructural modifications in plant. To this end, this work presented a model based on a multi-view analysis of a plant: Traffic Flow View (describing the structure and decomposition of the environment and the way vehicles interacted with this environment) and View Family of Building (identify the product exchange  
620 among buildings of the plant based on the available traffic information). Each view is modeled in terms of holons reducing the complexity and size of the model. The integrated model of the simulator was the fusion of the view models. Plant is recursively decomposed to build holons and holarchy. Road network is recursively divided into links, segment and exchange point. The authors defined  
625 satisfaction and affinity to allow holons to dynamically change their roles. To validate their model, the authors presented a 3D representation of the simulated world through a virtual reality platform in their laboratory.

Hadfi and Ito [52] proposed a holonic simulator of complex urban environment focusing on weather conditions. The idea of the proposal is the modeling  
630 of the simulator in terms of multiple independent layers. Each layer represents a complex network and operates autonomously with all its agents and components. Holonic paradigm in this model resides in the fact that the content of each layer is hierarchy in itself and all the components of the layers can interact according to the dynamics of the simulation. The presented results ensured  
635 the reproduction of realistic driving behaviors. In addition, results were given

faster and the simulator generated rich data-sets relative to the vehicles, the pedestrians, the drivers' actions, and the weather effect of the simulation map.

Abdoos et al. [2] proposed a bottom up method to build holarchy for a multi-agent urban area network based on graph theory. Agents are modeled using an indirect and weighted graph in which the weights denote the degrees of the dependencies between the agents. The algorithm of holons formation starts with an empty set of holons, and during execution algorithm, new holons are added either as new holons or by joining an existing holon. To evaluate the consistency of their method, authors proposed a quality measure based on the dependencies between the agents. In the case study of the paper, the intersections were modeled by nodes of graph and the roads by edges. The model has been tested on a road network with 18 intersections and 39 two-way links using Aimsun<sup>4</sup> traffic simulator. The results of the experiments showed that the model of Abdoos et al. [2] reduces the average delay time in comparison with a homogeneous method. The main drawback of this model is that the holarchy is composed of only two abstraction levels that is very simplistic. Moreover, the model is static. Abdoos et al. [1] extended the work of Abdoos et al. [2] taking into account the drawbacks of the previous model. To this end, the authors introduced holonic Q-learning to control the signals in traffic network. The proposed holonic Q-learning method was applied to learn signals timing in two holarchical levels. In the case study, the method has been applied on a network that contains 50 intersections and 112 two-way links. The experimental results of the method showed that the holonic Q-learning prevents the network to be over-saturated while it causes less average delay time and higher flow rate.

Esmacili et al. [31] proposed a method, inspired from social networks, to build the initial holonic structures of multi-agent network with a bottom-up approach. The prerequisite of the model is an unweighted undirected multi-agent network model. Their networked is presented as a graph such that vertices are the agents and edges are the interaction relationship between agents. Holonifi-

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<sup>4</sup><http://www.aimsun.com>

665 cation process starts with locating the agents that are eligible to play head role.  
 These head agents construct a basic holon in the lowest level of the holarchy.  
 Then, recursively, the other agents of the network attempt to join these basic  
 holons, based on their position in the network and the eligibility of their neigh-  
 bors. They use urban traffic signal control to evaluate the quality of the holons  
 670 constructed. This method has been tested on an urban traffic road network  
 containing 25 intersections and 31 connecting roads. They use average traffic  
 delay time to compare their method and the method of Abdoos et al. [2], say-  
 ing that their method causes relatively lower delay time for the vehicles in the  
 traffic network and postpone the saturation time of the traffic than the method  
 675 of Abdoos et al. [2].

#### 5.4. *Street light*

Moghadam and Mozayani [74] proposed an intelligent management of street  
 lighting based on traffic rate. The proposed architecture controls the lighting  
 system by intelligent agents using holonic organization mounted on the traffic  
 680 infrastructure. In this model, the studied area is divided into some geographical  
 holons such that each holon consists of some streets approximately situated in  
 one geographical district. There are two holarchical levels in centralized and  
 distributed form such that at the high level, there are geographical holons and  
 their heads with strategic task, and at the low level, there are learner agents  
 685 with tactical task in geographic holon. The heads of the geographical holons  
 classify the low-level learner agents into two groups: high consumption holon  
 and low consumption holon according to the streets adjacency and kind of their  
 consumption. The adjacent streets which have the same energy consumption  
 rate are in one holon. Therefore, the head supervises the consumption rate  
 690 of holons. The main goal of their approach is to manage street lighting to  
 optimize the energy consumption. The experiments are made on a small traffic  
 network consisting of 17 main two-way streets and 6 junctions. The results of  
 experimentation showed that the energy consumption of the normal mode is  
 high than the energy consumption using holonic architecture.

695 *5.5. Traffic coordination and forecasting*

Traffic Radar [83], is a holonic traffic coordination system focusing on the distributed and dynamic nature of traffic. Traffic Radar is composed by an extension PROSA named PROSA++ architecture and the delegate multi-agent system (D-MAS) pattern. As PROSA, PROSA++ identifies four holons types  
700 viz. ResourceInstance holon (reflects a specific part of the traffic infrastructure), ResourceType holon (holds policies regarding a specific resource entity or a group of resources), ProductInstance holon (corresponds to a request for a trip in the traffic network, originating from a traffic user) and ProductType holon (holds all policies regarding a traffic user or a group of users). Network is  
705 represented by a set of two distinct ResourceType holons: Link holons and Node holons while Vehicle holons are represented by ProductInstance holons. D-MAS is an architectural pattern that allows a holon to delegate a responsibility to a swarm of lightweight ant agents to support this holon in fulfilling its functions. The experiments of Traffic Radar show the ability to forecast traffic flows and  
710 densities based on individual user intentions.

## 6. Analysis of the Survey

After presenting some relevant papers that use holonic paradigm for traffic and transportation, this section seeks to discuss the relevance of this paradigm in traffic and transportation modeling. As stated before, holonic paradigm in  
715 traffic and transportation has two main orientation: HMAS and HMS. Figure 4 outlines the proportion of HMAS and HMS of the papers presented above. As shown on this figure, most of the papers focus on HMAS. This observation can be explained by Table 1. In fact, the scope of HMAS is wider than the scope of HMS which is generally restrained to manufacturing.

720 As stated before, transportation is an activity where someone or something is moved between point A and B by one or several modes of transportation (air, water, or ground transport) while traffic refers to the flow of different transports within a roads' network. Figure 5 evaluates the proportion between

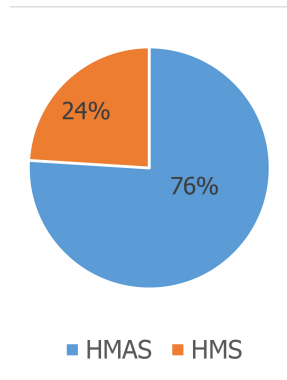


Figure 4: HMAS vs. HMS proportion in traffic and transportation

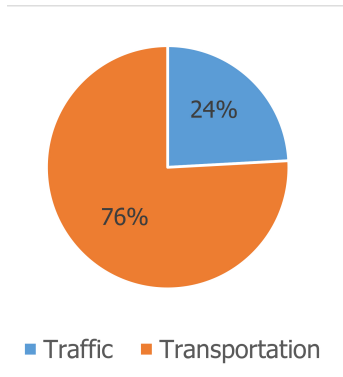


Figure 5: Traffic vs. Transportation proportion in holonic modeling and simulation

725 traffic and transportation using holonic paradigm. As shown on this figure, most  
of the papers presented above focus on transportation. This is explained by the  
fact that fleet management and modeling environment are the main scientific  
research paths for holonic traffic and transportation models. Moreover, most of  
the papers using holonic approaches, which focus on modeling and simulation  
traffic flows do not focus on pure traffic flow. Modeling and simulation of traffic  
730 flow using a pure holonic paradigm remains a challenge.

### 6.1. *Why holonic paradigm in traffic and transportation?*

According to the definition of a complex system given by Simon [95], traffic and transportation systems are large scale complex systems because: (i) they are composed of heterogeneous entities; (ii) the number of entities composing them is very high; (iii) interactions between these entities are non-linear; (iv) they are fundamentally and geographically distributed; (v) there are several levels of details or abstraction of traffic observations [98]. To deal with the high complexity of traffic and transportation systems, a suitable technology must be used. Holonic paradigm seems to be a good technology to deal with large scale traffic and transportation issues for several reasons:

6.1.a) **Reduction of complexity:** One of the most useful features in terms of reduction of complexity for the designer of a multi-agent system is that a whole task can be broken down into a variety of specific sub-tasks, each of which can be solved by a specific agentified problem solver. This reduction of complexity is also followed by the well-known divide-and-conquer algorithm where a problem is recursively breaking down into two or more sub-problems of the same or related type, until these become simple enough to be solved directly. Multi-agent system, divide and conquer etc. are therefore examples of approaches allowing to reduce the complexity of a given system. Like MAS, divide-and-conquer, holonic paradigm allows to divide the system in perspectives or views to reduce the number of entities involved and decrease the complexity of the process [88]. This can be done through a top-down building method orientation (a holon is recursively divided into several sub-holons).

6.1.b) **Emergent properties:** Another feature that is considered for the designer of a complex system is emergent behavior which is raised from the interactions between entities. Holonic paradigm can lead to emergent properties [46, 31]. This can be done through bottom-up building method orientation (several holons interacts together to form a super-holon). In fact, toward the top of the holarchy, behaviors become more

and more strategic while toward the bottom of the holarchy, behaviors become more and more operational. The emergent properties of the system rise toward the top of the holarchy.

6.1.c) **Multilevel observation.** Holonic paradigm allows to represent a com-

765       plex system under several views ranging from microscopic to macroscopic  
through mesoscopic. In general, the multilevel modeling and simulation  
of road traffic for instance [70, 84], combine simultaneously different road  
traffic models in one model. Each model is associated with part of road  
network. The goal of hybridization is to manage the transition of the  
770       models at the border. Most of the multilevel models focus therefore only  
on two abstraction levels (micro and macro, macro and meso, meso and  
micro). As stated before, the particularity of holonic paradigm in mul-  
tilevel modeling of traffic and transportation is that it can combine the  
three main abstraction levels (micro, meso and macro) in the same model  
775       according to a point of view.

6.1.d) **Link observation levels.** Although it is widely recognized that the

presence of groups influences microscopic and aggregated pedestrian or  
vehicles dynamics, a precise characterization of the phenomenon still calls  
for evidences and insights [25]. In fact, although several works analyzed  
780       the influence of group behavior on the individual, there is still need for ad-  
ditional insights, for instance on the spatial patterns assumed by groups  
in their movement and in general on the interaction among different fac-  
tors influencing overall vehicles dynamics [25]. A holarchy is an effective  
solution to link micro and macro level [40] to understand the influence  
785       on macro to the micro level.

6.1.e) **Dynamic switch between observation levels.** Holonic paradigm al-

lows to switch dynamically into representation (micro, meso, or macro)  
according to several criteria like visualization, computational resources  
etc. [98, 1]. Holonic paradigm allows to maintain the best compromise



790 between simulation accuracy and available resources [46]. Moreover, abstraction levels are not fixed a priori but depend on the application.

6.1.f) **Scaling.** As stated before, while microscopic models, agent-based models cannot scale [82], holonic paradigm can scale [46]. Holonic paradigm becomes therefore a suitable approach to deal with large scale distributed  
795 phenomena like traffic and transportation [46, 88].

6.1.g) **Flexibility.** As presented in section 5, holonic paradigm can be coupled with other scientific methods like organizational model [40] mathematics model [21], petri net model [76], physic law [46, 52], reinforcement learning [1], graph-based model [59] to name a few.

800 6.1.h) **Smart technology.** Integration of intelligence is very important nowadays in traffic and transportation field with the emergence of Intelligent Transportation System. Holonic paradigm is already used in the modeling and simulation of smart traffic and transportation system [108, 92, 2, 31] which make it a suitable approach for modeling and simulation of  
805 large-scale smart traffic and transportation of tomorrow.

6.1.i) **Stability.** Holonic paradigm covers aspects of both hierarchical and heterarchical control approaches [91]. The resulting architecture has a high degree of self-similarity, which reduces the complexity to integrate new components and enables easy reconfiguration of the system [17]. Moreover, the holonic architecture offers off-line and on-line flexibility that  
810 makes it possible to implement the required adaptability of the system [91]. In fact, off-line structural flexibility of the holonic architecture allows the implementation of features of heterarchic and hierarchic organization [91]. The on-line structure allows aggregation (resp. disaggregation) of holons into a new super-holon (resp. in several sub-holons)  
815 during the system-life.

6.1.j) The works presented in Section 5 show that holonic paradigm can reduce the computational cost [46], the average delay time of traffic light [2, 1],

and energy consumption [74, 53]. Additionally, it can forecast traffic  
820 flows and densities [83], and provides greater flexibility and robustness  
[67, 68] to name a few.

## 6.2. How to design traffic and transportation models using holonic paradigm?

To model traffic and transportation system using holonic paradigm in literature, several approaches are presented:

825 6.2.a) Approach of Giuseppe et al. [50], Liu et al. [68], Philips et al. [83] (noted A in Table 4): In this approach, a predefined configuration of holons is presented a priori according to a point of view. The kind of holons are defined a priori, the composition of each holon is known and the interconnected scheme is defined a priori. In the example of holarchy  
830 depicted by Figure 2 on page 9, all the holons of the holarchy i.e. holons at level 0, 1, 2 and 3 are defined a priori, and then the interaction schema between these holons is also defined. In this approach, holons can have different behavior i.e. holons at level 0 can have a different behavior of holons at level 1 for example. Some of these models are based on PROSA.

835 6.2.b) Approach of Gaud et al. [46], Galland and Gaud [40], Versteegh et al. [108], Salido et al. [92] (noted B in Table 4). The goal of this approach is to find the same behavioral model or the same algorithm for both the individuals and the group. Since individuals and groups have the same behavior, the self-similarity of behavior of groups and individuals is  
840 directly exploited at different abstraction levels to build the holarchy and to simulate the system. In the example of holarchy depicted by Figure 2, all holons belonging at level 0, 1, 2 and 3 exhibit the same behavior. In order words, super-holons and sub-holons of the holarchy exhibit the same behavior. The holarchy is structured and restructured based on  
845 the self-similarity property sharing by holons. Although this approach may ease the simulation process, its main drawback is finding the same

behavior for both individuals and groups because individuals and groups do not use the same time scale and features variables.

6.2.c) Approach of Abdoos et al. [1], Esmaeili et al. [30] (noted C in Table 4).

850 In this approach, the life-cycle of holonic model consists of two stages:  
(i) building the initial holarchy and (ii) controlling its structure against internal, and external stimuli during its lifetime. The initial holarchy represents the structure configuration of holonic model at time  $t = 0$ , while the control structure against internal and external stimuli represents the  
855 life of holonic model at time  $t > 0$ . In the example of holarchy depicted by Figure 2, all holons belonging at level 0, 1, 2 and 3 are defined at time  $t = 0$  as well as the initial interaction schema between them at time  $t = 0$ . Then, at time  $t > 0$  this initial interaction schema evolves as well as the holons themselves according to the policy defined by the de-  
860 signer. Although this approach may ease holonification (initial holarchy), its main drawback is to manage self-organization over time particularly for a highly distributed and open system like traffic and transportation.

6.2.d) Approach of Galland and Gaud [40], Galland et al. [41] (noted D in Table 4).

The idea that underlies this approach is that a system can be  
865 conceived in terms of an organized society of individuals in which each agent/holons plays specific roles and interacts with other agents/holons. The building of HMAS consists of two steps: (i) building the organizational model (organizational model offers several advantages [35] and can contribute to facilitate the design of holonic model), (ii) building  
870 the holonic model (the holonic model is derived from the organizational model). The advantages of this approach is to take into consideration the advantages of the organizational model (modularity, multiple architectures, heterogeneity of languages, application safety and reusability). However, the process of derivation of a holonic model from an organiza-  
875 tional model is not standardized, need a different adaptation depending on the case study and the moving from the organizational model to the

holonic model is not guaranteed a priori.

These approaches can be combined in modeling and simulation of a system which shows again the flexibility of holonic paradigm.

880 *6.3. What are the holonification design orientations of traffic and transportation application models?*

Holonification can be made through bottom-up approach, top-down approach or fixed configuration of holons a priori.

*6.3.1. Top-down holonification approach*

885 Top-down design methodology approach also named “system level” or “step-wise refinement” defines the system objectives as modules, then it breaks them into smaller and smaller set of modules, tasks or systems to accomplish theses objectives [82]. Top-down design methodology follows therefore a “divide-and-conquer” paradigm, in which the global mission is decomposed into a series of  
890 local tasks for each agent-based on their individual sensing and actuating capabilities, and accomplishment of the local missions ensures the satisfaction of the global specification via synchronized or partially synchronized multi-agent coordination [94]. In holonic paradigm, top-down holonification approach identifies levels and holons by progressively partitioning the entire system downscale  
895 [111]. In fact, holonification consists firstly of the modeling of the holon population (the highest super-holon of the system – the holon at level 3 in Figure 2); then the holon population from the top to bottom is recursively decomposed/divided/partitioned/split into several sub-holons according to a point of view. Top-down holonification methodology in holonic paradigm have several  
900 benefits:

- top-down holonification methodology reduces the complexity of system (a holon with a complex objective can decide to decompose into sub-holons and so on);

- 905 • top-down approach considers the requirements of the systems and the global conceptual design as the complete set of constraints/requirements that the solution must satisfy. These constraints/requirements must be satisfied by holon population. These constraints are very useful to guarantee the achievement of complex high-level global mission and motion plans by the system.
- 910 • top-down constraints and hierarchical linkages are also crucial for understanding and predicting the dynamics of most complex systems [111].

Top-down holonification approaches in holonic paradigm have also several drawbacks:

- 915 • top-down approaches suffer from the sensitivity to changes in user requirements and global conceptual design [16]. In fact, top-down holonification suffers from the sensitivity to changes in user requirements and conceptual design of holon population;
- top-down design methods lack flexibility and scalability in local control policy design due to their requirement for proper abstraction models [94]
- 920 • planning complexity rapidly becomes prohibitively high when the number of the partitions of holons in sub-holons become high, the increase of sub-holons and the levels of holarchy which further hampers the applicability of the abstraction-based methods in many practical circumstances.

### 6.3.2. Bottom-up holonification approach

925 The design process of bottom-up methodology also named “individual level” or “agent level” starts with the detailed modules or the available sub-systems and builds upon them to ultimately generate the system [82]. Bottom-up scheme involves therefore successively aggregating or grouping similar entities upscale [111]. Bottom-up design methodology is very popular for producing 930 autonomous, scalable and adaptable systems requiring minimal or no communication [24]. In holonic paradigm, bottom-up holonification approach starts

firstly with the modeling of atomic holons (agents of the system – holons at level 0 in Figure 2), then the interaction between these atomic holons generates a complex behavior. In fact, atomic holons interacts to form a group of atomic  
935 holons called their super-holon at the immediate higher abstraction level of the system. In other words, holons join/aggregate/regroup/unite together to form a super-holon at the immediate higher abstraction level. This process is repeated at each abstraction level until the holon population. Bottom-up holonification approach in HMAS has several benefits:

- 940 • bottom-up holonification approach leads to emergent properties without a formal specification of a global behavior. In fact, a set of holons with a simple behavior interact together to form a super-holon with a complex behavior. Towards the top of the holarchy lies emergent behavior;
- bottom-up holonification approach scales well [94]
- 945 • the focus is on autonomy and ability to cooperate that leads bottom-up holonification approach closer to the real-world complex system.

The main drawback of bottom-up holonification methodology is the lack of formal performance guarantees [94]. Because there is no global conceptual design, global constraints/requirements that solution must satisfy, bottom-up  
950 holonification cannot guarantee in advance a particular desired global behavior of the system. Holon population may not have the desired specific behavior.

### 6.3.3. *Predefined configuration of holons*

In holonic paradigm, the prefixed configuration of holons means that the structure of holarchy or/and the interconnected scheme of a given complex sys-  
955 tem is known a priori by the designers of the system. In general, in this approach, all the holons of the system are identified in advance, and whole/part observation relationship (or containing/contained observation) of these holons are also identified a priori. The main advantage of this approach is its ease because there is no management of the structure of holarchy during the life-system. The

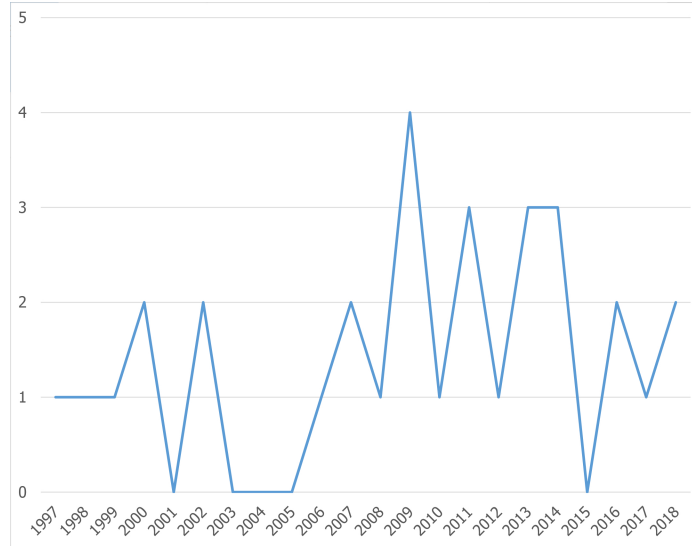


Figure 6: Time evolution of research papers using holonic paradigm in traffic and transportation

960 management of the holonic model becomes therefore less difficult. In contrary, the main drawback of this approach is the rigidity of the holarchy that leads a non-reusable system.

#### 6.4. What are the drawbacks of holonic paradigm in traffic and transportation?

Figure 6 presents the evolution of research papers using holonic paradigm  
965 over time and Figure 7 presents the spatial distribution of these papers.

As presented by Figure 6, the holonic paradigm applied to traffic and transportation has received little attention from researchers. In fact, the research papers per year varies from 0 to 4 that is very small and leads therefore to the following questions.

- 970 • Why there are few research papers using holonic paradigm in traffic and transportation?
- What are the main difficulties for holonic paradigm in traffic and transportation?

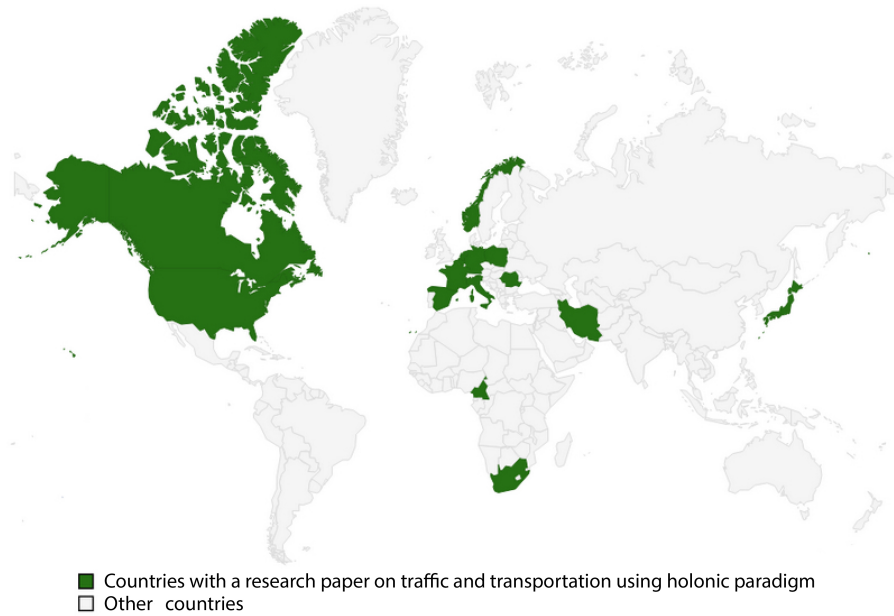


Figure 7: Spatial distribution of research papers using holonic paradigm in traffic and transportation

- Is too complex holonic paradigm for traffic and transportation modeling and simulation?
- Is suitable holonic paradigm to model traffic and transportation?

These questions raise up the drawbacks and the difficulties of the use of holonic paradigm to model and simulate traffic and transportation application. These difficulties can be explained by the following:

6.4.a) **Lack of standard methodology:** While holonic paradigm in manufacturing system has PROSA as a reference architecture, holonic paradigm in traffic and transportation does not have neither a reference architecture nor a standardized framework/protocol. Each author proposes his model that leads to a multiplicity of the models. The authors of ASPECS methodology and CRIO metamodels intended to present their model as the reference. Nevertheless, although ASPECS and CRIO are widely



cited in scientific literature, these models have not been accepted as a standard by the scientific community as shown by Table 4. For a successful application and deployment of holonic paradigm in traffic and transportation, standardized methodologies, protocols and/or metamodels are essential.

6.4.b) **Insufficient experimentation:** In the reviewed papers in this paper, some of the implementation are usually at the prototype stage or not completed. Experimental results are therefore under construction and results are, most of the time, basic with virtual data as shown by Figure 8 (see Table 7 in Appendix A and Table 4 in Appendix B for more detail). In these conditions, it's difficult to really measure the impact of holonic paradigm in traffic and transportation, and holonic paradigm still remains immature.

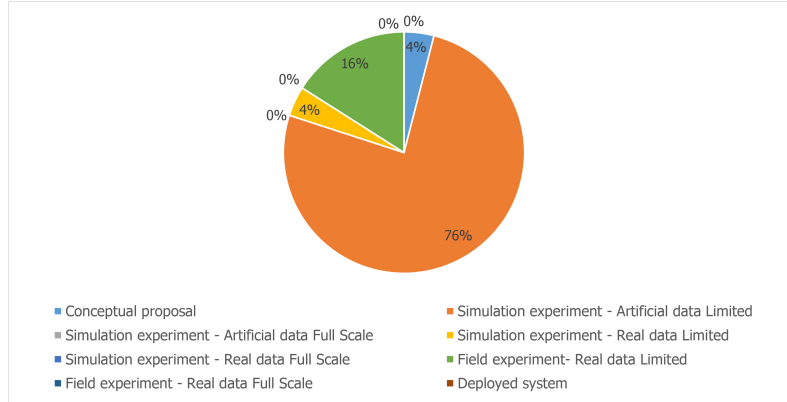


Figure 8: Maturity of holonic paradigm in traffic and transportation modeling

6.4.c) **Lack of real world, visual and realistic application:** In fact, while there are several visual realistic applications based on agent-based technology and microscopic modeling and simulation freely available on Internet<sup>5</sup>, there are none or very few visual realistic applications based on

<sup>5</sup>[www.traffic-simulation.de](http://www.traffic-simulation.de)

holonic paradigm to represent traffic and transportation. The real application of a real and concrete traffic and transportation is therefore questionable.

6.4.d) **Cost of holarchy management:** Modeling a highly dynamic system using holonic paradigm is a challenge. In fact, if the system is too dynamic (with too fluctuating state), the holonic system can spend more time managing the holarchy than running the system.

6.4.e) **Limited scope:** Holonic paradigm in traffic and transportation is widely used in scientific area (academia and research institute) as shown by Figure 9. To be more attractive, holonic paradigm must be extended to other communities like companies.

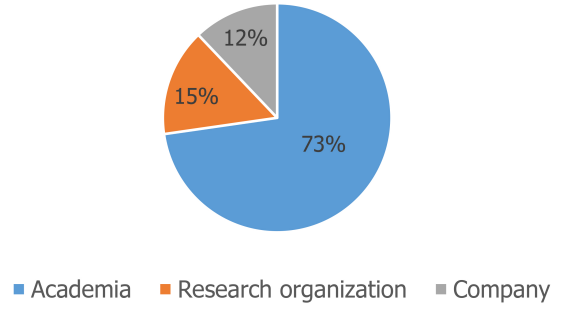


Figure 9: Area activity of holonic paradigm in traffic and transportation

## 6.5. Open issues

Several open issues are presented in this section in modeling and simulation of traffic flow and transportation using holonic paradigm.

6.5.a) **Sub-microscopic models:** Holonic models in traffic simulation focus only on micro, meso, macro levels. However, it can be interesting to focus on the submicroscopic level as well. In this case, it will be possible to include the behaviors of the entities' components, e.g. the mechanical

components of a car, to simulate the physical motion of the agents in a more realistic way.

1025 6.5.b) **Multilevel models of traffic:** Most of the multilevel models in literature for traffic flow modeling and simulation [70, 14] do not use holonic paradigm. However, we advocate that the use of holonic paradigm can provide a step to understand congestion because the modeling of multilevel models of road traffic flow using holonic paradigm can link several levels of detail and congestion is an emergent phenomenon which arises  
1030 from the low level of detail.

6.5.c) **Integration of norms:** In traffic application, the integration of norms can be an added-value to build the holarchy following application-dependent knowledge and rules. The use of norms allows to control, regulate, coordinate and cooperate of various entities involved in the system. The  
1035 concept of norms manages therefore permissions, obligations and prohibitions of entities involved and be implemented in traffic and transportation through the Highway Code management. This issue may be solved by the deepening and extension of the works of Missaoui et al. [72, 73]. This approach should enable the integration of the traffic regulations within  
1040 the HMAS.

6.5.d) **Considering the driver behavior:** Several works focus on the driver behavior, but none using holonic approach to the best of our knowledge. It is interesting to consider the driver behaviors in holonic approach, especially when facing the self-similarity of the holons' behaviors.

1045

6.5.e) **Optimization:** Optimization is still an open issue in holonic systems. In fact some research questions related to holonic systems are still open like how to improve the performance of holonic systems? How to realise a dynamic control adaptation with holonic systems? How to combine  
1050 for example the global production optimisation with agile reaction to

unexpected disturbances? To address these open issues, ADACOR architecture [63] allowing agile and adaptive manufacturing control and his extensions [10, 9] can be a path of solution.

1055 6.5.f) **Modeling large scale, distributed and open system:** Since traffic is open and highly dynamic, holonic approach can be applied in situations when traffic is stationary like peak hour, congested traffic, platoon, convoy. This affirmation needs a validation.

## 7. Conclusion

1060 The paper provides a comprehensive overview of holonic paradigm applied to traffic and transportation. To this end, the paper critically reviews relevant papers related to traffic and transportation modeling and simulation using holonic paradigm. Then, the benefits, drawbacks and the need of holonic paradigm in traffic and transportation are discussed. An overview and these models is also presented. Holonic paradigm research methodology requires further efforts in modeling of individuals (vehicles, pedestrians) and a consolidation of the approaches pursued by different research groups (especially those focusing on environment and fleet management).

1070 Future works include the modeling of the multilevel model of individuals, particularly vehicles, with holonic paradigm, the modeling of large scale, distributed and open systems through holonic paradigm, and the proposition of other multilevel indicators that will consider the spatio-temporal properties of the system and the driver behaviors.

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**Appendix A: Grades of the framework for describing holonic paradigm maturity – Inspired by Davidsson et al. [27]**

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1.	Conceptual proposal
2.	Simulation experiment
2.1.	Artificial data, 2.1.1. Limited, 2.1.2. Full-scale
2.2.	Real data, 2.2.1. Limited, 2.2.2. Full-scale
3.	Field experiment, 3.1. Limited, 3.2. Full-scale
4.	Deployed system

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Table 3: Maturity classification framework inspired by Davidsson et al. [27]

**Appendix B: Summary of Traffic and Transportation Models based on Holonic Paradigm**

Models	Holonic paradigm	Motion domain	Holder	Holonic observation	Holonic homogeneity	Holonic methodology	holonic coupling approach	Experimentation and/or modeling tools	Maturity	Contribution of holonic methodology	Goal of the model
Gaud et al. [47, 46]	HMAS	Transport	Academia	Moderated group	Affinity	B, D	Force-based model	ASPECS, Janus, Java	2.1.1.	Reduction of computational cost	Pedestrian simulation; optimization i.e. best compromise between simulation accuracy and computational resources
Tchappi et al. [100]	HMAS	Traffic	Academia	Moderated group	Closeness	C, D	Graph-based model	SARL, Janus	2.1.1.	Reduction of computational cost	Model multilevel snapshot road traffic
Tchappi et al. [101]	HMAS	Traffic	Academia	Moderated group	density (spatial closeness)	C	based on DB-SCAN	SARL, Janus	2.1.1.	Reduction of computational cost	Model multilevel snapshot road traffic
Liu et al. [67, 68]	HMS	Transport	Academia, Research Organization		Specialization	A	Based on PROSA, CNP	QUEST, Delphi	2.1.1.	Improves performance, provides greater flexibility and robustness	Fleet management, manage material handling
Roulet-Dubonnet et al. [91]	HMS	Transport	Academia, Research Organization	Federation, moderated group	Holons predefined organization	A	based on Babiceanu [7] framework, PROSA	QUEST	1.	Increase flexibility and scalability	Fleet management
Moghadam and Mozayani [74]	HMAS	Transport	Academia	Moderated group	Street geographical adjacency	C	Reinforcement learning	Aimsun, C++	2.2.1.	Reduction of electrical energy consumption	Smart management of street lighting
Abdoos et al. [2]	HMAS	Transport	Academia	Fusion	Adjacency	C	Based on graph theory	Aimsun	2.1.1.	Reduces the average delay time	Smart traffic signal control management, road network modeling
Abdoos et al. [1]	HMAS	Transport	Academia	Moderated group	Adjacency	C	Graph-based model, Q-learning	Aimsun	2.1.2.	Prevents network saturation, Reduces delay time	Smart traffic signal control management, road network modeling
Esmacili et al. [31]	HMAS	Transport	Academia	Moderated group	Adjacency, neighbors eligibility	C	Graph-based model, centrality concept	Aimsun	2.1.1.	Reduction of delay time, postpones saturation time of traffic	Smart traffic signal control management, road network modeling
Rodriguez et al. [87, 88]	HMAS	Traffic, transport	Academia, company	Moderated group	Satisfaction, affinity	D	Divide and conquer methodology	Madkit	2.2.1.	Scaling, decision support system	Modeling and simulation of large scale plant including inside traffic, chain production optimization
Galland and Gaud [40], Galland et al. [41]	HMAS	Transport	Academia	Moderated group	Place, zone	B, D	Physics laws (energy)	JASIM, Janus, ASPECS	2.2.1.	Scaling, compromise accuracy – computational resources	Environment model for crowds 3D simulation, airport simulation
Hadfi and Ito [52]	HMAS	Traffic, transport	Academia	Federation	Specialization	A		OpenStreetMap	2.2.1.	Scaling	Simulation of environment taking into account weather conditions
Traffic Radar	HMS	Traffic	Academia		Specialization	A	Based on PROSA, D-MAS	Erlang	2.1.1.	Forecast traffic flows and densities based on individual user intentions	Traffic coordination, traffic flow prediction

TeleTruck	HMAS	Transport	Research organization	Moderated group	Components matching	C	based on ECNP, IN-TERRAP	Oz	2.2.1.	Increases efficiency and transparency; reduction of traffic congestion, air pollution and energy consumption	Fleet management, driver scheduling
Gambardella et al. [43]	HMAS	Transport	Academia, Research organization	Moderated group	Components matching	C	Intermodal Planning and Negotiation Protocol	MODSIM III	2.2.1.	Scaling	Fleet management, planner and simulator for intermodal transport
Gołacki et al. [51]	HMAS	Transport	Academia	Moderated group	Optimization algorithm	C	Based on CNP	JADE	2.1.1.	Decrease costs for cases with narrow time windows	Fleet management; modeling and optimization of transportation requests
Koźlak et al. [59]	HMAS	Transport	Academia	Fusion, Moderated group	Optimization of goal function	C	Graph-based model	JADE	2.1.1.	Optimization	Fleet management
Giuseppe et al. [50]	HMAS	Transport	Academia, company, research organization		Specialization	A	Designed using UML, OWL, Fact++ reasoner	Visual Studio, C++, C#, SQL Server	3.1.	Allow rental plans and preventive maintenance	Diagnosis systems for fleet monitoring
Salido et al. [92]	HMAS	Transport, traffic	Academia	Federation, moderated group	Neighborhood	A, B	Using Pallottino algorithm	Java	2.1.1.	Secure approach to manage critical situations	Fleet management, route planning
Versteegh et al. [108]	HMAS	Transport, traffic	Academia	Federation, moderated group	Neighborhood	A, B	Graph location representation	Borland Delphi	2.1.1.	Scaling	Fleet management, route planning
Mortellec et al. [76]	HMAS	Transport	Academia, company	Federation, moderated group	Specialization	A, C	Divide and conquer methodology	EMAPS (Experimental Multi-Agent Platform)	3.1.	Give faster results	Doors fault diagnosis systems of a railway transportation system.
Fadil et al. [34]	HMAS	Transport	Academia, company	Federation, moderated group	Specialization	A, C	Based on ISO 13374		3.1	Increases on-board diagnostic, optimize maintenance	Fleet monitoring
Ciufudean and Filote [21]	HMS	Transport	Academia		Specialization	A		Based on Petri nets	3.1.	Less time consumption; increases safety and reliability	Railway traffic control, traffic jam problems, control and schedules distributed systems
Van Belle et al. [107]	HMS	Transport	Academia		Specialization	A		Based on PROSA	2.1.1.	Deal with disturbances	Control of chain conveyor
Borangiu et al. [12]	HMS	Transport	Academia		Specialization	A	(SOA) Service-Oriented Architectures, CNP	JADE, ILOG 6	2.1.1.	Long term scheduling workshift optimization	Fleet management for public transport services

Table 4: Comparison between traffic and transportation models using holonic paradigm

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