



Dynamic Multilevel and Holonic Model for the Simulation of a Large-Scale Complex System with Spatial Environment : Application to Road Traffic Simulation

Igor Tchappi Haman

► To cite this version:

Igor Tchappi Haman. Dynamic Multilevel and Holonic Model for the Simulation of a Large-Scale Complex System with Spatial Environment : Application to Road Traffic Simulation. Other. Université Bourgogne Franche-Comté; Université de Ngaoundéré (Cameroun), 2020. English. NNT : 2020UBFCA004 . tel-03226048

HAL Id: tel-03226048

<https://theses.hal.science/tel-03226048>

Submitted on 14 May 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



THÈSE DE DOCTORAT EN CO-TUTELLE

DE L'ÉTABLISSEMENT UNIVERSITÉ BOURGOGNE FRANCHE-COMTÉ, FRANCE

PRÉPARÉE À L'UNIVERSITÉ DE TECHNOLOGIE DE BELFORT-MONTBÉLIARD

École doctorale n°37 Sciences Pour l'Ingénieur et Microtechniques

ET DE L'UNIVERSITÉ DE NGAOUNDÉRE, CAMEROUN

Doctorat d'Informatique

par

IGOR TCHAPPI HAMAN

**Dynamic Multilevel and Holonic Model for the Simulation of a Large-Scale
Complex System with Spatial Environment
Application to Road Traffic**

Thèse présentée et soutenue à Belfort, le 13 mai 2020

Composition du Jury :

RUICHEK YASSINE	Professeur à l'UTBM	Président
BERTELLE CYRILLE	Professeur à l'Université Le Havre	Rapporteur
MANDIAU RENÉ	Professeur à l'Université Polytechnique Hauts de France	Rapporteur
BOISSIER OLIVIER	Professeur à l'École des Mines de Saint-Étienne	Examineur
ABBAS-TURKI ABDELJALIL	Maître de conférences HDR à l'UTBM	Examineur
MORVAN GILDAS	Maître de conférences à l'Université d'Artois	Examineur
GALLAND STÉPHANE	Professeur à l'UTBM	Directeur de thèse
KAMGANG JEAN-CLAUDE	Maître de conférences HDR à l'Université de Ngaoundéré, Cameroun	Co-directeur de thèse

To

**Anne Clarisse Poubè
Marie Nadège Makam**

ACKNOWLEDGEMENTS

I would first like to thank Cyrille Bertelle and René Mandiau for agreeing to be my thesis reviewers. I thank them for their relevant comments on the manuscript and their participation on my thesis jury.

I would also like to thank Yassine Ruichek for presiding over the defense and Abdeljalil Abbas-Turki, Gildas Morvan, Olivier Boissier to be part of my jury.

Thanks to Stéphane Galland who was more than a this thesis director. He was resilient in the face of the lengthy paperwork involved in the completion of this manuscript. I thank him for his kindness and the time he sacrificed to see these works succeed.

I thank Jean Claude Kamgang, for his patience and scientific rigour without which this manuscript could not have been completed. I hope this book will cover part of my immense debt to him.

I thank also Vivient Corneille Kamla who provided stimulating advice, guidance and encouragement to me every step of the way.

I would like to thank Caroline Delamarche for her support during these years. I would like also to thank all the members of CIAD laboratory of UTBM, in particular Yazan Mualla and Hui Zhao. I would like to thank all the members of LAMEX laboratory of the University of Ngaoundere, in particular Jaurès Fotsa, Etienne Ndamlabin and Dimitry Ngounou.

Thank you to all those who have shared my daily life during these years like my family and my friends (Diderot Cidjeu, Jean Louis etc.) and more.

CONTENTS

I	Context and State of the Art	1
1	Introduction	3
1.1	Context and motivation	3
1.2	General Problem	5
1.3	Thesis Goals and Contributions	6
1.4	Thesis plan	7
2	Multilevel Modeling and Simulation	9
2.1	Introduction	9
2.2	Large-Scale Complex System	9
2.2.1	Notions of System and Complexity	10
2.2.2	Complex System	11
2.2.2.1	Definitions of Complex System	12
2.2.2.2	Emergence in Complex Systems	12
2.2.2.3	Characteristics of Complex Systems	14
2.2.3	Large-Scale System	15
2.2.4	Large-Scale Complex System	16
2.2.4.1	Examples of Perspectives Depicting the Same System . . .	17
2.2.4.2	Example of Large-Scale Complex System: the Road Traffic	17
2.3	Modeling & Simulation of Large-Scale Complex System	19
2.3.1	Framework for Modeling and Simulation	20
2.3.1.1	Source System	20
2.3.1.2	Models	20
2.3.1.3	Simulation	22
2.3.2	Multilevel Modeling and Simulation	23

2.3.2.1	Multilevel Modeling	24
2.3.2.2	Multilevel Simulation	25
2.3.2.3	Issues of Multilevel Modeling and Simulation	26
2.4	Conclusion	27
3	From Monolevel to Multilevel Models of Road Traffic	31
3.1	Introduction	31
3.2	Classification Criteria for Traffic Simulation Models	32
3.2.1	Level of detail of Traffic	32
3.2.2	Time Management	33
3.2.3	Stochastic or deterministic models	33
3.3	Monolevel Models of Traffic	34
3.3.1	Microscopic Models	34
3.3.1.1	Car-following models	35
3.3.1.2	Lane Change Model	38
3.3.2	Mesoscopic Models	39
3.3.3	Macroscopic Models	39
3.3.4	Benefits and Drawbacks of Monolevel Traffic Models	40
3.3.4.1	Benefits and Drawbacks of Microscopic Models	40
3.3.4.2	Benefits and Drawbacks of Mesoscopic Models	41
3.3.4.3	Benefits and Drawbacks of Macroscopic Models	41
3.3.5	Summary of Monolevel Model of Traffic	41
3.4	Multilevel Models of Traffic	42
3.4.1	Static Multilevel Models of Traffic	43
3.4.1.1	The Model of Mammar et al. [84]	43
3.4.1.2	The Model of said EL Hmam et al. [126]	43
3.4.1.3	The Model of Moutari and Rascle [99]	44
3.4.1.4	The Model of Burghout et al. [18]	45
3.4.1.5	The Model of Bourrel and Lesort [11]	45
3.4.1.6	Summary of Static Multilevel Models of Traffic	46

3.4.2	Dynamic Multilevel Models of Traffic	47
3.4.2.1	The Model of Sewall et al. [129]	48
3.4.2.2	SIMILAR/JAM-FREE	48
3.4.2.3	Summary of Dynamic Multilevel Models of Traffic	48
3.5	Conclusion	49
4	Holonic Multi-Agent Systems	53
4.1	Introduction	53
4.2	Multi-Agent Systems	54
4.2.1	Fundamentals of MAS	54
4.2.1.1	Definition of agent concept	54
4.2.1.2	Definition of MAS	55
4.2.2	Drawbacks of MAS	57
4.3	Focus on Multilevel Agent based Modeling	57
4.4	Holonic Multi-Agent System	60
4.4.1	Fundamentals Definitions	60
4.4.2	Communication in HMAS	64
4.4.3	Comparison between MAS and HMAS	64
4.5	Modeling a Large-Scale Complex System using HMAS	67
4.5.1	Holonic Organization	67
4.5.2	Direction for holonification	68
4.5.3	Grouping and Splitting Criteria	69
4.5.4	Multilevel indicators	70
4.6	Conclusion	71
II	Dynamic and Holonic Multilevel Model of Large-Scale Traffic	75
5	Research Methodology and Contributions	77
5.1	Introduction	77
5.2	Hypothesis and Research Questions	78
5.2.1	RQ1: Holonic Organization	79

5.2.2	RQ2: Holonification Methodology	80
5.2.3	RQ3 : Grouping/Splitting Criterion	80
5.2.4	RQ4: Multilevel Indicator	81
5.3	Contributions	82
6	Holonification of a Large-Scale Traffic System	85
6.1	Introduction	85
6.2	Fusion as the Holonic Organization of Traffic	86
6.3	Upward Density-Based Holonification	86
6.3.1	The Benefits of the Grouping of Similar Entities of Traffic	87
6.3.2	The Framework of Building The Upper Levels of Holarchy	88
6.3.3	Density Based Grouping Criterion	90
6.3.3.1	Basics Notions of DBSCAN algorithm	91
6.3.3.2	Benefits and Drawbacks of DBSCAN	93
6.3.3.3	Summary of Density Based Criterion	94
6.3.4	Building The Upper Levels of Holarchy	94
6.3.4.1	Formal definitions of the HMAS of Traffic	95
6.3.4.2	Algorithms To Build Upper Levels	97
6.4	Downward Probabilistic Distribution Holonification	98
6.5	Conclusion	100
7	Dynamicity within The Holonic Multilevel Model of Traffic	103
7.1	Introduction	103
7.2	Framework For Dynamic Management of Holarchy of Traffic	104
7.2.1	Interaction Model Between Holons when no Transition	106
7.2.2	Interaction Model Between Holons when Transition to Upper Level	107
7.2.3	Interaction Model Between Holons for the Transition to Lower Level	108
7.2.4	Holons Behavior Algorithms	109
7.2.4.1	Traffic Holon Algorithm	109
7.2.4.2	Cluster Unit Holon Algorithm	110
7.3	Dynamic Management of Holarchy for Traffic Simulation	110

7.3.1	Traffic Simulation in No Transition Case	111
7.3.1.1	Perception Model: update neighborhood	111
7.3.1.2	Behavioral Model	112
7.3.2	Traffic Simulation in Transition to Upper Level Case	113
7.3.2.1	Similarity Distance Between Traffic Holons	113
7.3.2.2	Multilevel Indicators	113
7.3.2.3	States Estimation from Lower to Upper Levels	114
7.3.3	Traffic Simulation in Transition to Lower Level Case	115
7.4	Discussion	116
7.5	Conclusion	117
8	Application to Highway Simulation	121
8.1	Introduction	121
8.2	Experimentation Tools	122
8.2.1	SARL	122
8.2.2	Janus	123
8.3	Case study	124
8.3.1	Results from A to B	125
8.3.2	Results from B to C	126
8.3.3	Results from C to D	126
8.3.4	Compromise Simulation Accuracy/Availability of Computational Resource	126
8.4	The performance of the Proposals	131
8.4.1	H-DBSCAN Performance	131
8.4.2	Holarchy Management Performance	132
8.5	Discussion	133
8.6	Conclusion	133
III	Conclusion and Perspectives	135
9	General Conclusion	137

9.1	Summary of the Contributions	137
9.2	Perspectives	139
9.2.1	Integration of Lane Change Model	139
9.2.2	Limitation of Interval of Run-Time of Upper Levels	139
9.2.3	Deployment with Real Data	140
IV	Bibliography	141
V	Annex	165
A	Publications of the Author	167
A.1	Publications that are related to this PhD thesis	167
A.2	Other Contributions	169

I

CONTEXT AND STATE OF THE ART

INTRODUCTION

1.1/ CONTEXT AND MOTIVATION

The growth of population and the increase of the number of users on the road network constitute nowadays a considerable source of various problems. The impact of the massive number of cars on road is felt in term of security, financial, environmental and public health to name a few. In the environmental area, vehicles produce emissions of greenhouse gases and pollutant, as a result of increased congestion and recurrent accordion phenomena [69, 73]. The economic consequences of fuel consumption and time lost in traffic jams are not left out. The cost of congestion alone in European Union (EU) is estimated at €100 billions in 2007 [24] and it is still worsening. In fact, congestion costs U.K. nearly £8 Billion and costs each American 97 hours, \$ 1,348 a year in 2018 according to INRIX¹. Added to this, incidents and accidents are caused by the deterioration of traffic conditions. According to the World Health Organization, road traffic injuries are the tenth most cause of death worldwide in 2016 [154]. More efficient, more safer and more sustainable transportation solutions are therefore essential for the functioning and prosperity of modern societies. One of the intuitive solution to improve traffic is related to the construction of new roads or/and widening existing ones. However this solution has several drawbacks. In fact, it is not always possible to construct or widen roads due to the lack of space specially in urban area. Moreover, construction of new roads or/and widening the existing ones requires a high cost of investment and contributes to increase pollution. It is therefore useful to optimize the use of road infrastructure.

Modeling and simulation of road traffic is a suitable solution allowing optimization and improvement of traffic [64]. During the past decades, several approaches have been proposed to model and simulate traffic due to its characteristics. In fact, traffic is a large-scale complex system [16, 64] i.e. (i) traffic is composed by several autonomous and

¹ INRIX is a private company which collects anonymized data on congestion, traffic incidents, parking and weather-related road conditions from millions of data points daily in over 80 countries.
www.inrix.com

heterogeneous entities, (ii) the number of entities composing the traffic is very high and interactions between these entities are non-linear, (iii) traffic is geographically and fundamentally a distributed phenomenon, (iv) there are several levels of detail of traffic observation. Among these approaches allowing to model and simulate traffic, we can cite:

- **Microscopic models of traffic [107, 147, 23, 52]:** describe the individual evolution of vehicles. Microscopic models are considered to be the most accurate and closest to the real behavior of the system because they bring out individuals and interactions between them, which creates the dynamics of the system. Moreover, microscopic models bring out emerging phenomena such as congestion [78]. However, the high accuracy of microscopic models is also their main weakness because this accuracy requires too many parameters those are difficult to calibrate. Furthermore, microscopic models require a high computational cost, especially when the number of interacting entities increases like for large-scale traffic.
- **Mesoscopic models of traffic [17]:** describe the traffic entities at a high level of detail, but their behavior and interactions are described at a lower level of detail. Two main approaches to design mesoscopic models of traffic could be found in the literature: one in which individual vehicles are not taken into account because the vehicles are grouped in packets or platoons that move along the links, and one in which the dynamics of the flows is determined by the simplified dynamics of individual vehicles [64]. As advantage, mesoscopic models tend to fill the gap between the aggregate level approach of macroscopic models (see below) and the individual interactions of the microscopic models. As drawback, as macroscopic models, mesoscopic models exhibit coarse behavior i.e. they are less accurate.
- **Macroscopic models of traffic [92, 80]:** consider traffic as a flow by analogy with the mechanics of fluids. Macroscopic models of traffic usually characterize the global behavior of traffic by speed, flow and density. Macroscopic models have the advantages of being simple, easy to handle, because they have few parameters, which makes the calibration and validation of models easier than for the other types of models. In addition, the execution time of macroscopic models is usually considered as acceptable. However, macroscopic models exhibit the coarsest behavior i.e. they are the most less accurate.

As stated before, large-scale complex system is composed by several autonomous and heterogeneous entities interacting in a non linear way. The characteristics of large-scale complex system such as the autonomy and the heterogeneity of the entities, the non linearity graph of interactions are widely taken into account in microscopic, mesoscopic and sometimes in macroscopic modeling. However, the hierarchical characteristics of

large-scale complex systems has not widely taken into account by these modeling approaches. One modeling approach mainly addressing the hierarchical characteristic of large-scale complex system is the multilevel modeling. Multilevel modeling can refer to the combination of microscopic, mesoscopic and/or macroscopic models within the same model. Multilevel modeling enables to mix the advantages of microscopic, mesoscopic and/or macroscopic modeling and therefore enables the representation of the system from several perspectives [143]. Moreover, multilevel modeling enables to link different representations (micro, meso, macro) and thus increases the understanding of the relationship existing between these representations [55]. Furthermore multilevel modeling and simulation enables the scalability of the system [50]. This thesis focuses on multilevel modeling of large-scale complex system with spatial environment such as road traffic.

1.2/ GENERAL PROBLEM

Combining several levels of detail (micro, meso, macro) within the same model requires managing hybridization (the transitions between these levels of detail) [50]. To manage hybridization of multilevel models of large-scale complex system with spatial environment such as traffic systems, the common methodology proposed in literature [11, 126] is first to divide the road network in sections such that each level of detail is associated to one section of the road network and then to manage transitions between these representations at the border of the road network by aggregation/disaggregation of vehicle(s) for example [84]. This methodology has several drawbacks:

- The levels of detail to be combined are chosen a priori either micro-macro, micro-meso or meso-macro. In addition, the combination is made only between two levels of detail. It can be interesting to combine more than two levels of detail in the same model.
- Decomposition of road network in sections is made a priori i.e. by experts. In fact, the success of this kind of model depends on the quality of the decomposition of road network in sections and the suitable choice of the level of detail associated to each section of road.
- The multilevel model is static because once a level of detail is a priori associated to a section of road network, this configuration cannot evolve over the time.

According to Bouha et al. [10], to be able to observe congestion or to find the exact location of a jam in a macroscopic section, a dynamic multilevel model is required. Dynamic multilevel models of large-scale complex with spatial environment system such as road traffic enables the same road section to be modeled by either micro, meso or macro, and

enables a transition between these representations during run-time. However, although revising some drawbacks of static multilevel models of traffic, according to Bouha et al. [10], there are very few works dedicated to dynamic multilevel modeling of traffic. In [143], we have identified two works available in literature: the work of Sewall et al. [129] and SIMILAR/JAM-FREE [3] those combines dynamically microscopic and macroscopic representations. However, microscopic representation is too far away from macroscopic representation and a direct transition from micro to macro or from macro to micro can sometimes leads to inconsistency [106]. A step transition through meso representation is advisable to increase the consistency of the transition process between micro and macro [105]. This thesis focuses on multilevel modeling allowing a dynamic combination of microscopic, mesoscopic and macroscopic representations. The general problem of this thesis is therefore:

GENERAL PROBLEM

How to build a dynamic multilevel model of large-scale complex system with spatial environment such as traffic system supporting a combination of microscopic, mesoscopic and macroscopic representations?

1.3/ THESIS GOALS AND CONTRIBUTIONS

The goal of this thesis is the proposition of a general dynamic multilevel model of large-scale complex system with spatial environment such as traffic system allowing a transition between microscopic, mesoscopic and macroscopic representations. To this end the thesis focuses on Holonic Multi-Agent System (HMAS) [53]. HMAS is a suitable paradigm for dynamic multilevel modeling and simulation [60]. HMAS structures a community of hierarchical agents (autonomous entity able to perceive their environment and to act on it), called holons. A holon is an agent that could be composed by other agents [53]. The holon concept allows agents to group together to create a higher-level agent named super-holons. A holon can also be break down into several lower level agents named sub-holons. The ability of holons to be composed and decomposed dynamically is used in this thesis to represent traffic entities at different representations i.e. from several perspectives.

The two main contributions of this thesis are:

- **A holonification model:** The main issue in deploying a HMAS is the building of the holonic model called holarchy. A holarchy can be structured from bottom to top (upward holonification) or from top to bottom (downward holonification). Both

upward and downward holonification models, allowing to structure the holarchy of the system are proposed in this thesis. On the one hand, to enable the upward holonification model, a density based similarity criterion is proposed to group entities sharing some characteristics. On the other hand, the downward holonification model is based on the Gaussian distribution.

- **A methodology for the management of the holarchy's dynamics:** To manage holarchy over time, a methodology allowing transitions between representations is proposed. It is based on the dynamic adaptation of the levels of detail during the simulation execution which enables to adapt the model to constraints related to the accuracy of the results or the available computing resources.

In addition, to validate the proposal, an application on highway is presented. In this application, simulation can migrate from microscopic representation to mesoscopic representation for example by the will of designer or by the simulation needs. The experiments are made on several scenarios to investigate how the proposal behaves.

1.4/ THESIS PLAN

The rest of this thesis is organized as follows. Chapter 2 presents the definitions and core concepts of both large-scale complex system and multilevel modeling and simulation. Moreover, one example of large-scale complex system that is road traffic is presented.

Chapter 3 presents approaches used to model and simulates traffic flow. Micro, meso, macro and multilevel models of traffic are presented. Their advantages and drawbacks are discussed. The need of further works on the dynamic multilevel models of large-scale complex system such as traffic system is highlighted.

Chapter 4 presents holonic multiagent systems, a suitable paradigm allowing the dynamic multilevel modeling. The philosophy followed by holonic multiagent systems and their key concepts are presented. The methodology to deploy a holonic multiagent system is also given.

Chapter 5 aims at positioning the thesis. A brief summary of the three previous chapters is given. Then we recall our problematic in order to highlight hypothesis and research questions of the thesis.

Chapter 6 outlines a model to hierarchize a population of similar vehicles. The holonification can be made from bottom to top or from top to bottom to build the hierarchy of holons. Moreover, both grouping and splitting criteria are defined for the holons.

Chapter 7 proposes a methodology to manage the proposed holarchy of large-scale system such as road traffic over the time. A methodology allowing a transition from one

level of detail to another is given. The added value of the proposed methodology is its dynamicity.

Chapter 8 presents an application of road traffic system on highway in order to evaluate and validate the contribution of the thesis. Experimentation and results are presented and discussed.

Chapter 9 concludes the thesis and provides several perspectives of this work.

MULTILEVEL MODELING AND SIMULATION OF LARGE-SCALE COMPLEX SYSTEM

2.1/ INTRODUCTION

The living world becomes more and more complex. In several domains such as geography, biology, economics, sociology, physics etc., the need of understanding phenomena of our direct (for example, terrestrial) or indirect (cosmos) environment is raised up. These phenomena or systems composed of interacting entities increase more and more on scale and complexity. To understand such large-scale complex systems their study is needed. To this end, since 1970s, several modeling and simulation practices have been developed for the study of large-scale complex systems in several scientific domains that share the common feature of explicitly representation of entities and their behaviors in a computational form with the power offered by today's computers.

This thesis focuses on modeling and simulation as an approach for the study of large-scale complex system. To this end, this chapter defines and presents both the fundamentals of the notion of large-scale complex systems and the modeling and simulation theory. Thus this chapter is structured as follows: Section 2.2 presents the fundamentals of large-scale systems and Section 2.3 presents the multilevel modeling and simulation theory.

2.2/ LARGE-SCALE COMPLEX SYSTEM

In real life, there are many natural, man-made and social entities that can be considered as large-scale complex systems. For example steelworks, petrochemical plants, power systems, transportation networks, water systems, and societal organizations can

be considered as large-scale complex systems [43]. One important question is to know why these previous systems are considered as large-scale and complex. In order to address this question, this thesis presents firstly the attempts of definition of the notions of system, complexity, complex system and large-scale system. Then the thesis presents the attempts of definition of large-scale complex system and an example of such kind of systems.

2.2.1/ NOTIONS OF SYSTEM AND COMPLEXITY

The advent of the systemic approach heralded a turning point in the history of science and its applications. The systemic approach can be considered as a general scientific paradigm, such as the Matter of Life or Society [48]. It offers a generic way to construct and present valid, relevant and rational representations of the most diverse, changing situations [48]. The systemic approach considers phenomena and problems as systems. The word *system*, which generally means “assembly”, derives from the Greek verb *sys-teo*, a word that was used to denote the action of attaching elements together. De Rosnay [30] defines the concept of system as follows (Definition 1):

Definition 1: System according to De Rosnay [30]

A system is a set of elements in dynamic interaction, organized around a goal

As outlined by Definition 1, a system is a set of interacting entities. A university is therefore an example of a system. In fact, university is composed by several colleges or/and faculties. Each college/faculty has classrooms, students, laboratories and many other objects, as entities. Each entity has its own attributes or properties.

The four major concepts that characterise the systemic approach are [48, 30]:

- **Interaction** is related to causality in a system: entities interact, i.e., they perform actions on other entities and are subjected to actions by other entities. In other words, two entities of a system have a bijective causal relationship, i.e. entity A influences entity B and vice versa.
- **Comprehensiveness** reflects the notion that everything cannot be reduced to the sum of its parts. This highlights both the interdependence of the entities of the system and the coherence of the whole. Therefore, a system is irreducible to its entities.
- **Organization** refers to the consideration of both the structure and operation of a system. Typically, the arrangement of the system's entities assures its functions and processes.

- **Complexity** refers to the number and characteristics of entities of the system, the uncertainties, the hazards specific to the environment of the system and the relationships between the notions of determinism and indeterminism.

Systemic approach is therefore a new way of seeing the Reality of the world, by trying to take into account its previously ignored characteristics such as instability, openness, fluctuation, chaos, disorder, vagueness, creativity, contradiction, ambiguity, paradox, which are the prerogative of complexity. In fact, the century of complexity is come. People write and talk more and more about complexity. The statement “I think the next century will be the century of complexity” done by the famous physicist Stephen Hawking in his millenium interview¹ became a prophecy widely cited. Stephen Hawking named the current century as the century of complexity. Complexity is a notion used in many domains such as philosophy, epistemology, physics, biology, theory of evolution, ecology, sociology, engineering, computer science. Depending on the domain, the notion of complexity can be very variable. In his book on introduction of complexity, Morin [95] attempted to give a general description of complexity.

Definition 2: Complexity according to Morin [95]

At first glance, complexity is a fabric (*complexus*: that which is woven together) of heterogeneous constituents that are inseparably associated: complexity poses the paradox of the one and the many. Next, complexity is in fact the fabric of events, actions, interactions, retroactions, determinations, and chance that constitute our phenomenal world. But then the complexity is presented with the disturbing features of the clutter, the inextricable, the disorder, the ambiguity, the uncertainty... Hence the need, for the knowledge, to put order in the phenomena by repressing the disorder, to discard the uncertain, that is to say to select the elements of order and certainty, to disambiguate, clarify, distinguish, hierarchize...

Morin [95] explains that complexity comes from the paradox between the accurate knowledge of an identified entity and the impossibility of understanding the phenomena induced by a set of these same entities evolving in a common environment. In fact, all the interactions (events, actions, feedbacks, etc.) between these entities cause a non-predictive behavior. In other words, understand perfectly an entity does not means the understanding of the system composed of these interacting entities.

2.2.2/ COMPLEX SYSTEM

Systems exhibiting complexity are generally called complex systems. They are everywhere and can be found in many fields such as social systems, global climate, ant

¹This interview was done on January 23, 2000 by San Jose Mercury News

colonies, economies, crowd movement, immune systems, disaster management system, and so on. Nowadays, with the emergence of complexity, the need of understanding complex systems is increasingly raised up. A precise definition of the complex system concept is therefore useful. There is no yet consensus on the definition of complex system and various definitions are available in literature. Each definition focuses on a specific property of a complex system.

2.2.2.1/ DEFINITIONS OF COMPLEX SYSTEM

This thesis considers the following definitions for complex system:

Definition 3: Complex System according to Sheard and Mostashari [131]

Complex systems are systems that do not have a centralizing authority and are not designed from a known specification, but instead involve disparate stakeholders creating systems that are functional for other purposes and are only brought together in the complex system because the individual entities of the system see such cooperation as being beneficial for them.

In Definition 3, Sheard and Mostashari [131] focus on the non-centralized characteristic of complex system because complex system is not run by a central authority, nor could it be, in most cases. Moreover, the authors note that requirements to be met by complex systems are unknown (unknown specification) because complex systems are dynamic systems whose behavior or evolution can not be predicted by a simple computation. In fact, the dynamic of a complex system can be subject to several states changes whose occurrences are difficult to predict. Complex systems are therefore difficult to understand and describe.

Definition 4: Complex System according to Simon [134]

Complex system refers to such system made up of several parts that interact in a non-simple way

In Definition 4, the author focuses on the non-linearity of interactions between entities composing the complex system. Moreover, the structure and behavior of a complex system is not easily inferred solely from the structure and behavior of its entities or parts because a global unforeseen behavior can arise through interactions of these entities called emergence.

2.2.2.2/ EMERGENCE IN COMPLEX SYSTEMS

Emergence in complex systems can be defined as follows (Definition 5):

Definition 5: Emergence according to Drogoul [33]

Emergence is a fuzzy, unclear and often decried concept. Emergence in complex systems generally denotes, the appearance of a global effect that is not deductible from the knowledge of local causes.

To the notion of emergence, Morin [94] associates the idea of surprise and novelty. Emergence refers to the qualities or properties of a system that have a novelty in relationship with the qualities or properties of its components considered in isolation or arranged differently in another type of system [94]. This idea of surprise provides a way to emphasize that emergence requires the look of an observer who is surprised by a phenomenon that he perceives. Emergence implies that the relationship existing between a global phenomenon and individual behaviors remains difficult to discern. Emergence occurs therefore when a system is observed to have properties its entities do not have on their own. These properties appear when the entities interact in a larger whole. A visual example of emergence that is the appearance of the global behavior in flocking phenomenon observed in migratory bird is shown by Figure 2.1. Emergence plays a central role in theories of integrative levels of complex systems.

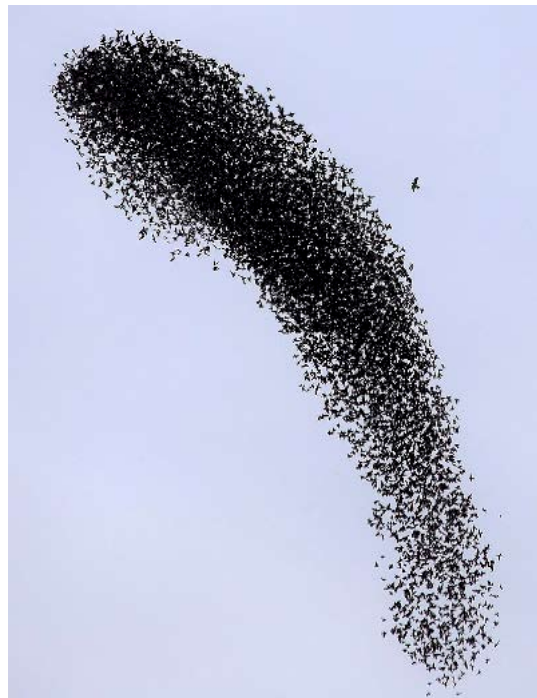


Figure 2.1: Example of emergence: the phenomenon of flocking birds. A global unforeseen behavior arise from the birds interaction.

Source: [https://en.wikipedia.org/wiki/Flock_\(birds\)](https://en.wikipedia.org/wiki/Flock_(birds))

Another example of emergence is congestion in road traffic (traffic jam). Congestion is a condition on transportation that is characterised by slower speeds, longer trip times, and

increased vehicular queueing. Figure 2.2 presents congestion in road traffic.



Figure 2.2: Example of emergence: the road traffic congestion which arise from interaction between vehicles

2.2.2.3/ CHARACTERISTICS OF COMPLEX SYSTEMS

Emergence is not the only characteristics of complex systems. There are several others characteristics those could be summarized as follows [131]:

- They are composed by many autonomous and heterogeneous entities (entities or parts of a given complex system can have different features).
- The graph of interaction of entities composing complex system is non-trivial that is to say non-linear.
- They exhibit self-organizing behavior by adaption to their environment as they evolve over time and space. This self-organization (spontaneous order) arises from local interactions between entities and no external control is needed.
- They can exhibit hierarchic structure (several level of organization).
- They can display emergent behavior that raises up from the actions and interactions of the individual entities.
- They have fuzzy boundaries. The boundaries of system can vary considerably according to context or conditions, instead of being fixed once and for all.

Due to the diversity of complex systems, their study is interdisciplinary. The engineering of complex systems is at the forefront nowadays and the study of complex system is generally made by experimentation or simulation (by a series of trials and errors).

2.2.3/ LARGE-SCALE SYSTEM

Large-scale systems are such kind of systems susceptible to failures caused not only by the software bugs but also by the scale of the system [27]. A typical example of the failure caused by the scale of the system is the crash happened in 2010. In fact, on May 6, 2010, U.S. stock markets underwent an extraordinary upheaval. On early in the afternoon, the Dow Jones Industrial Average began to decline. In 10 minutes, Dow Jones dropped by over 600 points representing the loss of about \$ 800 billion dollars of market value. During this sudden decline, the prices of several leading multinationals went insane. Share prices in companies that had been a few tens of dollars dropped to \$ 0.01 in some cases, and soared to values over \$ 100,000.00 in others. As suddenly as this upheaval occurred, it reversed itself i.e. within minutes, most of the loss was recovered. Share prices returned to levels close to a few percentage points of those they held before the upheaval. This suddenly upheaval was called “flash crash”. Several investigations were made in order to explain the crash. On September 30, 2010, a report was issued stating that the triggering event of the crash was a sell program to sell a total of 75,000 E-Mini S&P contracts (valued at approximately \$ 4.1 billions) on behalf of a fund-management company, executed with uncommon urgency. It has been argued that the consequences of this triggering event interacting with algorithmic trading rapidly buying and selling shares rippled out to cause the system-level failures [138]. The crash was not the outcomes of the software bugs but was caused by large interactions between independently managed software systems, which created unforeseen conditions for trading system owners and developers [138]. The 2010 flash crash is not the only example where failure were caused by the scaling

<i>Project</i>	<i>Problems</i>
Internal Revenue Service tax system modernization	In early 1997, the modernization project was cancelled, after expenditures of \$4 billion and 8 years.
Federal Aviation Administration air modernization	Project begun in 1981, major pieces of project were canceled, others are over budget The total cost estimate in 2004 was \$42 billion of work.
Bureau of Land Management automated land and mineral records system	After spending more than 15 years and approximately \$411 million, the program was canceled in 1999.
Bell Atlantic 411 system	On November 25, 1996, Bell Atlantic experienced a directory service outage for several hours after the database server operating system was upgraded and the backup system failed.

Table 2.1: Examples of past troubled large-scale systems [27]

of the system. There are other examples available [27] in literature. Table 2.1 presents some failures generated by the increasing of the number of entities in some previous projects.

One of the goals of the engineering of large-scale systems is to define the framework for their study in order to avoid phenomena like 2010 flash crash. Thus, the concept of large-scale system has to be defined. However there is not yet a universally accepted definition of the large-scale systems. Some authors consider large-scale systems as a subset of complex systems i.e. for them large-scale systems exhibit generally a complex behavior [153] while for others, it is possible for large-scale systems to exhibit a simple behavior i.e. a non complex behavior such as interacting particle systems [79, 113]. Anyway, usually, it can be said that a particular system is large-scale if it has one or more characteristics those are described in Definition 6.

Definition 6: Large-Scale System according to Soye et al. [140], Council et al. [27]

Large-scale systems are a particular type of dynamic systems having the following characteristics:

- **Large number of entities:** Large-scale systems are distinguished from other systems by the importance of the number of entities involved (thousands, millions, even billions);
- **Large number of interactions:** Entities interact between them and environment, and the number of these interactions is important;
- **Large size of the environment:** Entities within environment are geographically distributed.

Furthermore, the study of large-scale system with computer simulation bring out the challenge of computational resources [96]. A successfully study of large-scale system implies therefore also a suitable management of the computational resources.

2.2.4/ LARGE-SCALE COMPLEX SYSTEM

Several definitions are available in literature for the notion of large-scale complex system. In fact, there is no universal definition of large-scale complex system. This thesis considers the followings definitions:

Definition 7: Large-Scale Complex System according to Šiljak [133]

Large-scale complex system is characterized by its high dimensions (large number of variables), constraints in the information infrastructure, and the presence of uncertainties

In Definition 7, Šiljak [133] highlights the uncertainty property of large-scale complex system. In fact uncertainty refers to situations involving imperfect or unknown information. Thus, large-scale systems are difficult to predict.

Definition 8: Large-Scale Complex System according to Mahmoud [83]

Large-scale complex system is a system which is composed of a number of smaller constituents, which serve particular functions, share common resources, are governed by interrelated goals and constraints and, consequently, require more than one controllers.

In Definition 8, Mahmoud [83] highlighted some properties of large-scale complex systems. One property catch our attention: a large-scale complex system can be controlled by multiple number of controllers. This means that a large-scale complex system can to be modeled from several perspectives. A perspective (from Latin: perspicere meaning “to see through”) is a point of view or a representation of a system.

In order to well understand the concept of large-scale complex system, this thesis presents both examples of several perspectives depicting the same system is in Section 2.2.4.1 and example of large-scale complex system in Section 2.2.4.2.

2.2.4.1/ EXAMPLES OF PERSPECTIVES DEPICTING THE SAME SYSTEM

To illustrate the need of modeling a system from several perspectives, this thesis presents Figure 2.3 that outlines two different projections of a stack of two cubes, illustrating oblique parallel projection foreshortening (“A”) and perspective foreshortening (“B”). Projection A and projection B are complementary views of the stack.

In the same vein, even real or artificial phenomena can exhibit a behavior from several perspectives. One example is road traffic which exhibits a behavior from the perspective of individuals (outlined in Figure 2.4) and from the perspective of the whole (outlined by Figure 2.5).

2.2.4.2/ EXAMPLE OF LARGE-SCALE COMPLEX SYSTEM: THE ROAD TRAFFIC

Road traffic is an example of large-scale complex system. Road traffic is considered as a large-scale complex system because:

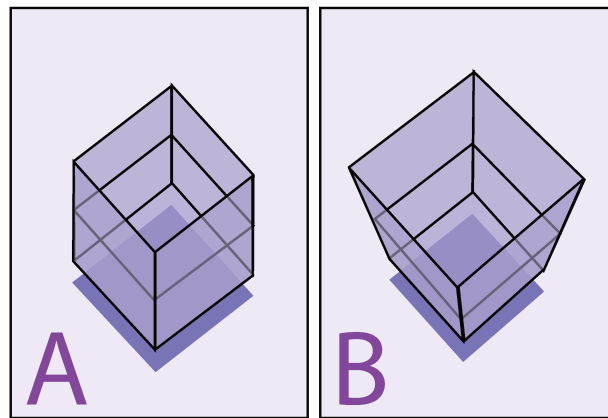


Figure 2.3: Two different projections of a stack of two cubes. Source: [https://en.wikipedia.org/wiki/Perspective_\(graphical\)](https://en.wikipedia.org/wiki/Perspective_(graphical))



Figure 2.4: Road traffic system from the perspective of the individuals (the vehicles). Source <https://france3-regions.francetvinfo.fr>

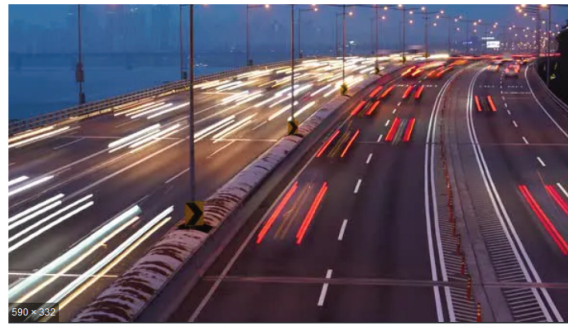


Figure 2.5: Road traffic system from the perspective of the whole (the flow). Source <https://videohive.net/item/city-night-traffic-flow/24089234>

- The entities composing road traffic are autonomous. In fact, the pair driver – vehicle is autonomous, independent, self-aware and exhibits often a selfish behavior.
- The entities composing traffic are heterogeneous. Road traffic is composed by bike, motorcycle, 3-wheels, car, trucks, etc. These vehicles do not drive with the same speed and space occupied by them is not the same.
- The number of entities and interactions involved is important: in 2016, there are 973,353,000 registered vehicles in the world [29]. According to their locations, these vehicles interact between them leading to an important number of interactions. Moreover, because selfish behavior of the drivers, interactions between them is non trivial nor non linear.
- The size of environment is large. Traffic is geographically distributed and covers a wide environmental size (rural area, urban area, town, country etc.).

- Traffic exhibits self-organization behavior. Platoon, congestion arise and disappear from interaction between vehicles without central management.
- Traffic exhibits hierarchic structure. As stated before, road traffic can be represented from several perspectives: microscopic (from the perspective of the individuals i.e. the pairs vehicle–driver), mesoscopic (from the perspective of the groups of vehicles, the platoons, the convoys), macroscopic (from the perspective of the whole i.e. the flow of vehicles).
- Traffic exhibits emergent behavior. Weather delay, platoons, congestion are behaviors arising from interaction between vehicles.

Figure 2.6 outlines road traffic as an example of large-scale complex system.

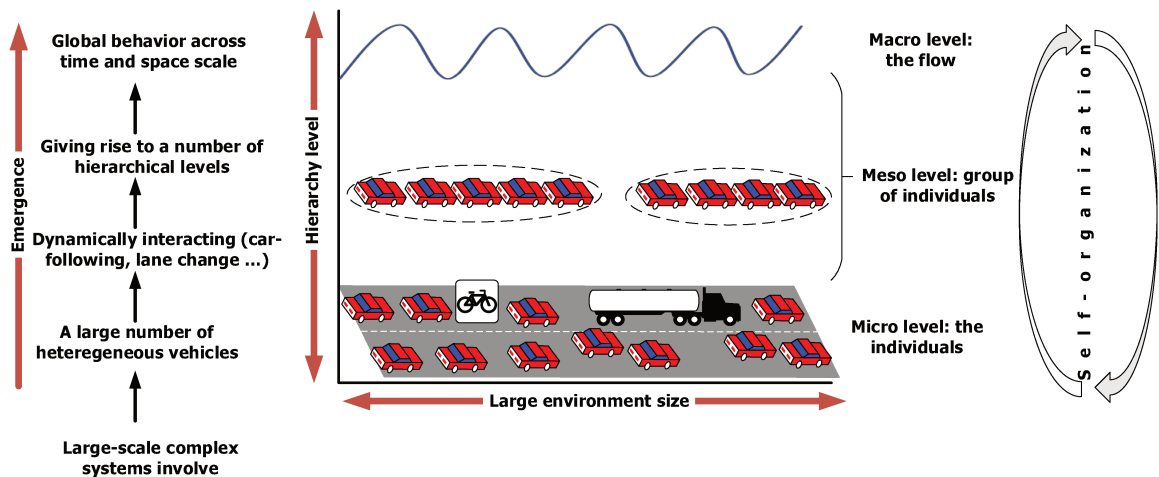


Figure 2.6: Road traffic, a large-scale complex system

Due to the complexity exhibited by a large-scale complex system, suitable approach is required for their study. Modeling and simulation is one of the important solution for their study [157]. More details of modeling and simulation is presented in the following section.

2.3/ MODELING AND SIMULATION OF LARGE-SCALE COMPLEX SYSTEM

This section presents the fundamentals of the modeling and simulation (M&S) theory (Section 2.3.1). In addition this section presents also the fundamentals of multilevel modeling and simulation (Section 2.3.2). In fact, as stated before large-scale complex system

can exhibit hierarchical behavior and thus it can be interesting to study these systems from several perspectives. Multilevel modeling and simulation could be considered as a tool for capturing this hierarchical behavior.

2.3.1/ FRAMEWORK FOR MODELING AND SIMULATION

Since several decades, several modeling and simulation practices have been developed in several fields of Science. M&S allow to understand, predict or even control real or virtual phenomenon [156]. In fact, M&S enable the study of real or virtual phenomena in laboratory in order to produce knowledge on it. Thus, M&S is appropriate for studying systems that can not be directly observed or measured [56].

Defining a framework for M&S is not a trivial activity. It is necessary to follow a certain approach. Research in this area has made M&S theory a complete science by offering theories, tools and vocabulary. Zeigler et al. [157, 156] have proposed a framework for M&S establishing entities and their relationships. The entities of the framework are source system, experimental frame (the conditions under which the system is observed or experimented), model, and simulator. Some of the entities of the M&S framework are presented in the following sections.

2.3.1.1/ SOURCE SYSTEM

M&S theory is not based directly on the system to be studied but on a simplification of it. The source system is the real or virtual environment to model. Source system represents a part of Reality circumscribed by the scientists [148]. It is viewed as a source of observable data, in the form of time-indexed trajectories of variables. The data are produced by observation, experimentation or other measurement mechanisms. Data can have different natures (qualitative or quantitative). The goal of M&S is to tend according to a point of view to the replica of source system through models. In fact, the core of M&S is the fundamental notion that models are approximations of the real world, as detailed in the following section.

2.3.1.2/ MODELS

Nowadays in scientific community, more and more researchers and scientists build, refine and compare their models. To understand why scientists and researchers spend much time on building, refining and comparing their model, a definition of this concept can be useful. There is currently no consensus on the definition of the term model. This thesis considers the following definitions of a model:

Definition 9: Model according to Treuil et al. [148]

A model is an abstract construction that makes it possible to understand the functioning of a source system by answering a question concerning it.

Definition 9 highlights the missions of the model. In fact, this definition highlights two of the main characteristics of a model those are: understand the source system and answer questions about it. For the first characteristic, understand the functioning of the source system enables the prediction of its evolution. For the second characteristic, a model captures only aspects of the source system needed to be answered. A model cannot therefore be used in general to answer any question about the source system that it represents, but only to the questions for which it was designed.

Definition 10: Model according to Zeigler et al. [156]

A model is a system specification, such as a set of instructions, rules, equations, or constraints for generating input/output behavior.

In Definition 10, a model is assimilated to a specification of source system. The definition in terms of system specifications has the advantage of having a solid mathematical foundation and precise semantics that everyone can understand unambiguously. Zeigler et al. [157] have defined several levels of specification (hierarchy of system specifications) that a model can reach. Levels of specification refers to a way of describing the system source that is different with the notion of perspectives presented above (cf. Definition 14).

The higher the level of specification, the more the model gives a detailed description of the source system:

- **Level 0 - observation frame:** The observation frame specifies how to stimulate the system with inputs, i.e. which variables must be observed, and how to measure them over time.
- **Level 1 - I/O behavior:** The I/O Behavior of a system is the collection of all I/O pairs gathered by observation. The time-indexed input/output are defined.
- **Level 2- I/O function:** The notion of state of the model is introduced as an intermediary to link inputs and outputs. Initial states are added to the specification.
- **Level 3 - state transition:** The dynamics of the model is highlighted by a definition of transitions between the states of the model.
- **Level 4 - coupled component:** The structure of the model is composed of a set of interconnected components.

A model can be static or dynamic. A model is static when it represents a source system at a given instant without taking into account its evolution over time. Inversely, a model

is said dynamic when it includes in its representation assumptions or rules relating to the temporal evolution of the source system. Static modeling is more rigid than dynamic modeling because it is a time-independent view of a system. Dynamic modeling is more flexible because the dynamic of the system can evolve over time. Due to the advantages of the dynamic modeling, the goal of this thesis is to propose a dynamic modeling of large-scale complex system with spatial environment.

2.3.1.3/ SIMULATION

Simulation is used in several disciplines such as manufacturing applications, project management, military applications, logistic supply chain and distribution applications, health care, transportation mode and traffic etc. Simulation can be used to test a hypothesis of the source system, verify it, or accredit the theory that was used to build it. Simulation can also be used to understand the functioning of the source system and therefore serve as support for decision making [157].

Like the concept of model, simulation does not have a consensual definition. Ören [111] has collected more than 100 different definitions of simulation [111] and about 400 different types of simulation [110]. This thesis considers the following definitions of simulation.

Definition 11: Simulation according to Treuil et al. [148], Cellier and Greifeneder [21]

Simulation is an experimentation performed on a model

Definition 11 allows to explain the link existing between a model and its simulation. Simulation consists of executing a model. Simulation allows to disturb the model over time by changing its states step by step according to its dynamics, while producing the outputs associated with each state. A simulation therefore generates information on the evolution of the system over time. In order to produce the dynamic of the system, simulation can use a tool called simulator. Simulator is a computer program capable of interpreting models and used to produce the desired disturbances on these models.

Definition 12: Simulation according to Law et al. [75]

Simulation is a set of techniques that employ computers to imitate – or simulate – the operations of various kinds of real-world facilities or processes.

Definition 12 states that the objective of the simulation is to imitate some real world phenomena. Therefore simulation can be applied to a wide range of real world phenomena. In the study of traffic system which is an example of real world phenomenon, simulation can be defined as follows:

Definition 13: Simulation of Traffic according to Champion [22]

Simulation of traffic mimics realistically the behavior and the interactions of real entities (cars, trucks ...) in order to reproduce as faithfully as possible the behavior of the traffic system

The ability of traffic simulation to emulate the time variability of traffic phenomena makes it a unique tool for capturing the complexity of traffic. As stated before, like traffic system, simulation can be applied to several others phenomena. To this end, two fundamental relationships have to be taken into account when designing a simulation [157, 156]:

- **Modeling relation:** The relation between a model, a system and an experimental frame. It defines the validity of the model, its ability to faithfully capture the system behavior within the extent demanded by the objective of the simulation study
- **Simulation relation:** The relation between a simulator and a model. It defines the correctness of the simulator, its ability to correctly simulate the model, to faithfully generate the model's output trajectory given its initial state and its input trajectory

Entities of the M&S framework, modeling relation and simulation relation and the links between them are presented in Figure 2.7.

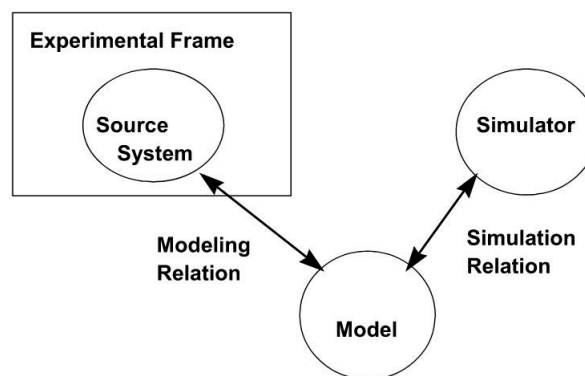


Figure 2.7: Framework of M&S and relationships [156]

2.3.2/ MULTILEVEL MODELING AND SIMULATION

Nowadays, multilevel M&S is more and more used for understanding large-scale complex systems [16, 143, 10, 96, 17, 11, 50]. In fact, large-scale complex system can exhibit a behavior at several scale and therefore to well understand their dynamics, one level of detail will likely not suffice. It can be interesting to combine several levels of detail of the system in order to observe the system from several perspectives.

Definition 14: Level of detail according to Morvan [96]

A level of detail (abstraction level or representation) is a point of view on a system, integrated in a model as a specific abstraction.

In this thesis, based on the definition of Morvan [96] the term level of detail, abstraction level, observation level and system representation follow the same idea [96] that is a point of view or a perspective of the system source. Taking into account several levels of detail in modeling a system enables the multilevel modeling of the system.

2.3.2.1/ MULTILEVEL MODELING

When a system is modeled from a single perspective, it is not possible to talk about multilevel modeling. Multilevel modeling involves at least two different levels of detail. This thesis considers the following definition for the concept of multilevel modeling.

Definition 15: Multilevel Modeling according to Morvan [96]

Multilevel modeling is the integration of heterogeneous models, representing complementary points of view, so called levels, of the same system.

In Definition 15, heterogeneity means that the multilevel model can be based on different modeling paradigms (differential equations, partial derivative equations, cellular automata, etc.), can use different time representation (discrete events, time step) and can represent processes at different spatial and temporal scales. In other words, multilevel modeling allows to combine several levels of detail within the same model. Usually, literature provide three main levels of detail for a system modeling those are:

- **Microscopic – micro – level (also called microscopic representation):** The perspective adopted is at the level of the individual entities composing the system. The dynamic of the system arises from interactions between individual entities composing it. The structure of the system is considered emerging from these interactions.
- **Macroscopic – macro – level (also called macroscopic representation):** The goal is to characterize the collective behavior of the entities composing the system through a set of variables. The simulation tries to represent the variations and changes of these variables over time. The perspective adopted by macroscopic representation is therefore at the system level. Macroscopic representation seeks to recreate the overall dynamic of the system.
- **Mesoscopic – meso – level (also called mesoscopic representation):** Mesoscopic representation is an intermediary representation between the microscopic

representation and the macroscopic representation. Mesoscopic level contains therefore both individual information and collective information.

There are several approaches available in literature for multilevel modeling [96, 19]. One of them is to specify the microscopic level and use observation of an experimenter to capture the macroscopic level [55]. This approach is called emergentist because it is single-level in design and bi-level in the analysis of behaviors produced [55]. This approach seems limited for some large-scale complex systems because some of them can not be understood without integrating several levels of detail and therefore can not be reduced to a purely emergent vision [55]. It therefore seems important to be able to integrate, within the same model, the descriptions of entities at different levels of detail corresponding to different perspectives of the system. To this end a combination in multilevel modeling of micro-macro, micro-meso, meso-macro or micro-meso-macro models can be interesting. Multilevel simulation have to manage over time this combining.

2.3.2.2/ MULTILEVEL SIMULATION

Multilevel simulation involves at least two different levels of detail during simulation.

Definition 16: Multilevel Simulation according to Gaud [50]

Multilevel simulation is a special type of simulation where the proposed model of the system integrates different levels of detail and where the tools necessary for its execution make it possible to make these different levels of detail coexist within a same execution and to ensure the transition between them according to defined constraints (dependent on the model or the experimental framework)

Usually, a multilevel simulation integrates a limited and fixed number of levels of detail. Two levels are very often considered: microscopic and macroscopic, microscopic and mesoscopic, mesoscopic and macroscopic. These models are usually dependent on the target application. In some approaches available in literature [84, 11], the environment is divided into zones and each zone is associated a level detail. The transitions are therefore performed at specific connection points. In other approaches [54, 126, 18], the levels of detail are fixed for the whole simulation, determined a priori by the designer based on his/her experience and the experimental results of previous simulations. Others approaches allow a dynamic adaptation of the levels of detail, for example to save computational resources or to use the best available model in a given context [46, 45]. More details on the dynamic adaptation of the levels of detail during simulation is provided in chapters 3 and 4.

Several patterns can be considered in order to enable the combination of heterogeneous levels of detail. They are initially proposed by Maudet et al. [90] and presented below.

- **Aggregation:** refers to the function whereby key figure values on detail level are automatically summed up or grouped at runtime and shown or planned on aggregated level.
- **Disaggregation:** refers to the function that automatically provides the details of a key figure value from aggregated level on detail level.
- **Hierarchization:** is used to establish a hierarchical relation between some entities.
- **Border:** is used when two environments are separated by an object belonging to the two environments. The role of the border is to prevent the passage from one environment to another.

2.3.2.3/ ISSUES OF MULTILEVEL MODELING AND SIMULATION

As stated before, multilevel M&S allows the combination of several levels of detail having different temporal and spatial scale in the same model. When several heterogeneous representations are considered within the same simulation, several issues need to be considered:

- **Compatibility (communication) between heterogeneous representations:** Microscopic, mesoscopic and macroscopic levels do not have the same features variable nor the same formalism for their representation. Therefore combining microscopic and macroscopic model for example in a same model required to deal with the compatibility (or interoperability, communication) between them. How to manage compatibility of heterogeneous representations during transition? How to convert the representations from one heterogeneous level of detail to another heterogeneous level of detail? How do heterogeneous models communicate? Transformation rules allowing to ensure this compatibility need to be defined [151, 19]. The compatibility between heterogeneous representations (differential equations, partial derivative equations, cellular automata, etc.) in multilevel M&S is one of the main concern [50].
- **Transition between levels of detail:** The issue of the consistency of the transition between heterogeneous representations is also a issue of multilevel modeling and simulation [50, 31]. In fact, the issue of the consistency of transition between heterogeneous levels of detail introduces new constraints for the design of a multilevel simulation those are: why to make a transition from one representation to another during simulation? when to make a transition from one representation to another during simulation? And how to make a transition from one representation to another during simulation? Furthermore, the transitions between the levels of detail

can be defined a priori at a specific points that is static multilevel model or can be dynamic according to the simulation constraints such as visualisation, computational resources etc.

A multilevel M&S has to address the previous issues depending on the application case. Thus, since this thesis is interested by the dynamic multilevel modeling and simulation of a large-scale system with spatial environment, the proposal has to answer the previous issues reminded here: why and when to make transitions? How to make dynamic transitions? This is done in the second part of this thesis.

2.4/ CONCLUSION

This thesis focuses on the modeling and simulation of large-scale complex system with spatial environment from several perspectives. To this end, this chapter presents two main notions those are large-scale complex system and multilevel modeling and simulation. In the first hand, definitions and the main properties of large-scale complex systems is presented. In fact, large-scale complex system is characterized by a high number of entities involved and a high number of non-trivial interactions between these entities, which produce uncertainties. Moreover, large-scale complex system can exhibit emergent behavior and therefore can be represented from several perspectives. Figure 2.8 presents a summary of large-scale complex system. In the other hand, multilevel M&S allows an integration of several heterogeneous representations (differential equations, partial derivative equations, cellular automata, etc.) within the same model. Thus, multilevel is a suitable approach enabling the representation of large-scale complex system from several perspectives. Figure 2.9 presents a summary of the multilevel M&S. The main issues to address to build a multilevel modeling and simulation of a large-scale complex system are:

- [Compatibility between heterogeneous representations](#)
- [Transition between levels of detail.](#)

Furthermore, road traffic was outlined as an example of large-scale complex system because road traffic is composed by many autonomous and heterogeneous entities interacting by a non trivial graph of interaction on large, spatial and open environment. Thus, road traffic is a typical example of large-scale complex system with spatial environment. The next chapter present some modeling approaches of road traffic available in literature.

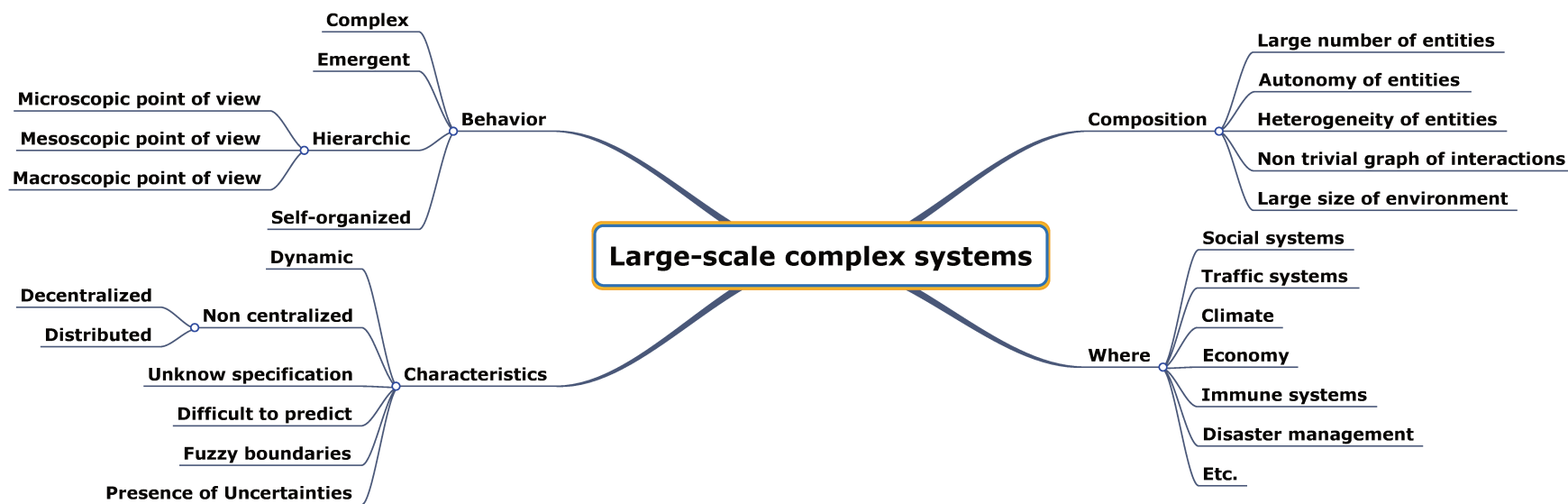


Figure 2.8: Summary of large-scale complex systems

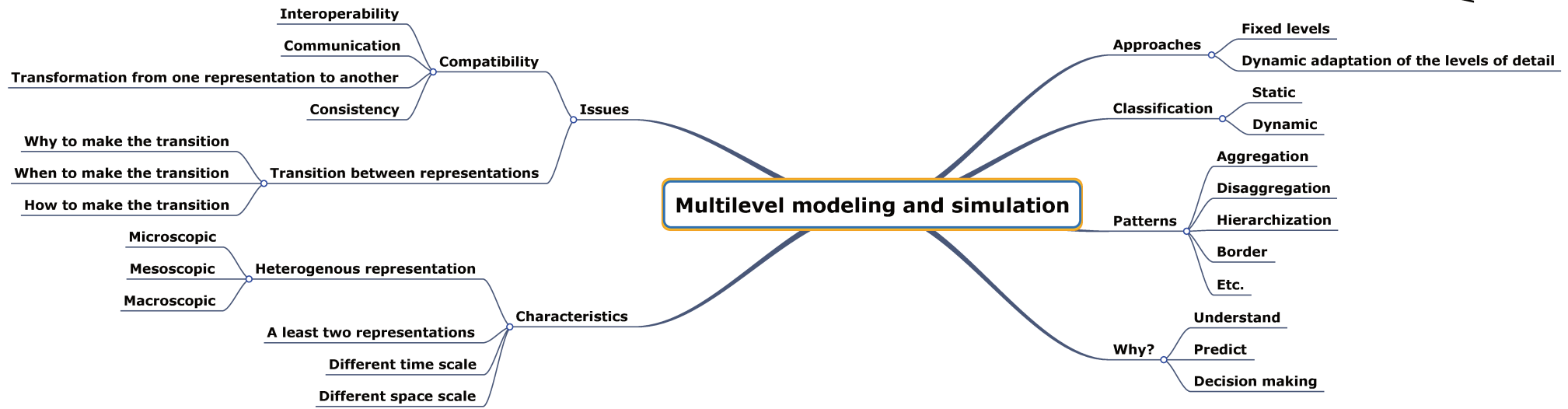


Figure 2.9: Summary of multilevel modeling and simulation

FROM MONOLEVEL TO MULTILEVEL MODELS OF ROAD TRAFFIC

3.1/ INTRODUCTION

The goal of this thesis is to propose a dynamic multilevel model of large-scale complex system with spatial environment. In the previous chapter, road traffic was outlined as an example of large-scale complex system because road traffic is composed by many autonomous and heterogeneous entities interacting by a non trivial graph of interaction on large, spatial and open environment. Thus as stated before, road traffic is a typical example of large-scale complex system with spatial environment. The application case of this thesis is road traffic.

Traffic system facilitates the movement of goods and people, provides access to employment, markets, education, care, recreation etc. Although very convenient for a user, with the exponential increase of the number of vehicles nowadays, traffic system is confronted with several social, environmental, safety, energy and economic issues... For example, referring to the road safety issue, more than 1.2 million people die each year from road traffic accidents worldwide and 20 to 50 millions non-fatal injuries occurs [112]. 90% of death occurs in low and middle income countries [112]. In Cameroon, a central African country, road accidents are the second leading cause of death, just behind malaria: more than 1,200 people die each year [108]. This illustrative example highlights the importance of efficient and safe road traffic management. M&S of road traffic can help to answer the problems of improvement of the conditions of movement of goods and people.

The goal of this chapter is to presents a brief state-of-the art of road traffic modeling and simulation. Road traffic can be modeled either by only one perspective called in this manuscript monolevel models of traffic, either by several perspectives (at least two different perspectives) named multilevel models of traffic. This chapter presents both monolevel and multilevel models of traffic. The advantages and drawbacks of these

models are also presented. Specifically, this chapter is organized as follows: Section 3.2 presents the classification criteria of traffic simulation. Section 3.3 presents some monolevel of traffic and Section 3.4 presents some multilevel models of traffic. Finally a conclusion ends this chapter.

3.2/ CLASSIFICATION CRITERIA FOR TRAFFIC SIMULATION MODELS

Traffic models can be presented in various forms and can be classified according to several criteria [32, 73]. In the following, three main criteria of traffic models classification are given those are the levels of detail of traffic observation, the time management and the part of the random in the model. This classification is used to present the traffic simulation models in the rest of this chapter.

3.2.1/ LEVEL OF DETAIL OF TRAFFIC

Let's remind that all traffic models do not have the same level of detail. In general literature provides three main levels of detail for traffic modeling and simulation: microscopic, mesoscopic and macroscopic levels:

- **Microscopic traffic models (cf. Figure 3.1):** Microscopic models (high fidelity) describe the entities of the system as well as their interactions at a high level of detail. Microscopic modeling of traffic is based on the description of the movement of each vehicle composing the flow. Microscopic models tends to be most close of the real behavior of vehicles.
- **Mesoscopic models (cf. Figure 3.1):** Mesoscopic models (mixed fidelity) are an intermediary representation between the macroscopic and the microscopic level. Vehicles are no longer considered individually but are grouped according to close and homogeneous traffic characteristics.
- **Macroscopic models (cf. Figure 3.1) :** Macroscopic models (low fidelity) have been used to understand and predict the formation of congestion and its propagation on the network. The goal of macroscopic models is to characterize the global behavior of traffic.

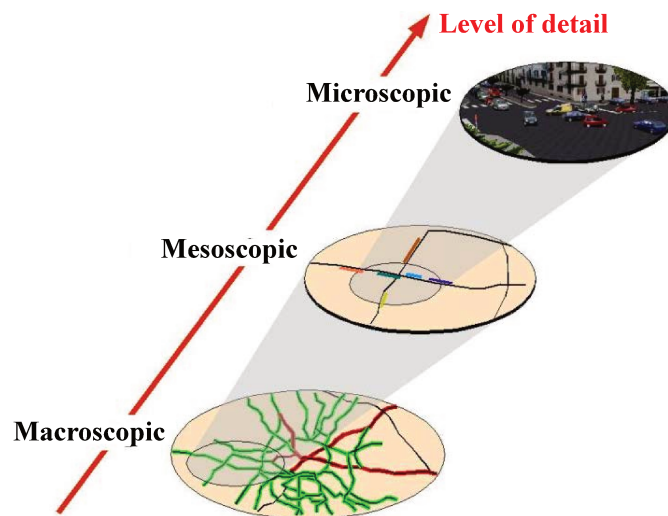


Figure 3.1: Levels of detail of traffic models [32]

3.2.2/ TIME MANAGEMENT

Time management is another classification criterion for traffic simulation. Literature provides usually two types of simulation models: continuous models and discrete models. In continuous models, the state variables of the simulated entities change in a continuous way, and not abruptly from one state to another. Continuous models give an infinite number of states of the system. A continuous representation of time is difficult to envisage on digital computer. This is the reason why traffic simulation tools use a discretization of time [32].

Discrete models assume that the state variables of the simulated entities change abruptly at certain moments of time. There are usually two types of discrete models in traffic simulation: discrete time models and discrete event models. On the first hand, discrete time models segment time into a succession of equal intervals called “time steps”. At each new time step, the model recalculates the different states and variables of the system. On the other hand, discrete event models remain constant until an event that causes the system state change occur. Discrete time models allow a fine representation of the evolution of the system. However, discrete time models can be expensive in computing time especially when the environment evolves very slowly from one simulation step to another [73].

3.2.3/ STOCHASTIC OR DETERMINISTIC MODELS

Deterministic models do not use any random variables or probabilistic functions. Interactions are defined through exact logical or mathematical relationships. Deterministic

models are therefore predictable because the system is understood and it is possible to predict what will happen. Inversely, stochastic models use the probability functions to conceptualize the interactions between the entities simulated. Stochastic models cannot be therefore entirely predicted [78]. The use of random variables in simulation models makes it possible to introduce a certain dispersion around the simulated phenomena.

As stated before, determinism has the benefit of the reproducibility of situations to be simulated. In this case it is easier to carry out experiments and to attest to the validity of the calculations made. However, in some cases it is better to have some degree of stochasticity in the simulation.

In some works, both stochasticity and determinism can be found in a simulation model. In fact, some parts of the model require the use of random variables while other parts are more easily modeled using deterministic models [32]. It is necessary to find a compromise between the determinism required to facilitate experimentation and the stochasticity that allows to introduce more realism into the simulation.

3.3/ MONOLEVEL MODELS OF TRAFFIC

Monolevel models of traffic refers to such models involving only one level of detail in modeling and simulation of traffic. In this category, as stated before in Section 3.2.1, literature provides three main levels of detail of traffic models: microscopic, mesoscopic and macroscopic models. In order to provide more details of each representation, this section is structured as follows: Section 3.3.1 presents some microscopic models of traffic. Section 3.3.2 presents some mesoscopic models and Section 3.3.3 some macroscopic models. Section 3.3.4 presents the advantages and drawbacks of each level of detail. Finally, a summary is given in Section 3.3.5.

3.3.1/ MICROSCOPIC MODELS

In microscopic model, each vehicle collects information in its environment (position of the surrounding vehicles, indications of the counters of the dashboard,...), treats this information, makes a decision and acts by operating a control of the vehicle. Microscopic models involve therefore the modeling of actions such as acceleration or deceleration of each driver named car-following models. Microscopic models allow also the modeling of lane changes.

3.3.1.1/ CAR-FOLLOWING MODELS

In car-following models, vehicles are described by a vector of state variables. Let us first note the time by the variable t . The others most common variables are:

- the position of the vehicle α at time t , denoted $x_\alpha(t)$,
- the instantaneous velocity of the vehicle α at time t , denoted $v_\alpha(t) = \dot{x}_\alpha(t)$,
- the acceleration of the vehicle α at time t , denoted $a_\alpha(t) = \ddot{x}_\alpha(t)$. Deceleration of the vehicle α at time t is denoted $b_\alpha(t) = \ddot{x}_\alpha(t)$, $b_\alpha(t) < 0$,
- the length of vehicle α , denoted l_α ,
- the bumper-to-bumper distance s_α between a leader vehicle $(\alpha - 1)$ and a follower vehicle α is defined by $s_\alpha = x_{\alpha-1} - x_\alpha - l_{\alpha-1}$.

Figure 3.2 presents the most common microscopic variables used in car-following models with a snapshot.

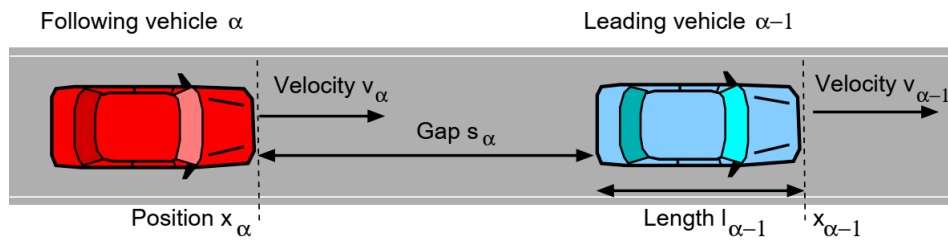


Figure 3.2: Some car following model parameters. The vehicle indices α are ordered such that $(\alpha - 1)$ denote the preceding vehicle. $\Delta x = x_\alpha - x_{\alpha-1}$ is the relative spacing between α -th and $(\alpha - 1)$ -th vehicles. The approaching rate (relative speed) is defined by $\Delta v_\alpha := v_\alpha - v_{\alpha-1}$ [69]

There are several microscopic car-following models available in literature. The followings presents some of them.

General Motor Model General Motors (GM) Group developed a series of models based on stimulus-response. Stimulus-response in car-following models has the following principle: a driver perceives a stimulus at a moment t and reacts to this stimulus with a certain time lag corresponding to his reaction time noted T . The response is proportional to the intensity of the stimulus, but also depends on the sensitivity of the driver to the stimulus. The basis equation is presented by Eq. 3.1.

$$Response(t + T) = Sensitivity \times Stimulus(t) \quad (3.1)$$

One of the first and simplest car-following model based on stimulus response is the model of Chandler, Herman and Montroll [23] developed at GM research laboratories. This model corresponds to the case when the response is represented by the acceleration or the deceleration of the follower vehicle and the stimulus is represented by the variation in the relative speeds. This model considers that the sensitivity is constant. The formulation is:

$$a_\alpha(t + T) = k\Delta v_\alpha(t), \quad \alpha = 1, 2, 3, \dots, N \quad (3.2)$$

where $T, k \in \mathbb{R}$ and $k > 0$. Parameter k is the sensitivity coefficient which measures the responsive intensity of driver to unit stimulus, and $N \in \mathbb{N}$ is the total number of vehicles on the considered road.

The model of Chandler et al. [23] do not take into account interdistance between two vehicles. To solve this problem, Gazis et al. [52] in 1961 proposed GHR model presented by Eq. 3.3.

$$a_\alpha(t + T) = k \frac{\Delta v_\alpha(t)}{\Delta x_\alpha(t)} \quad (3.3)$$

Edie [35] modified again the model assuming that the driver's response is more violent if its speed is high, regardless of the speed of the vehicle that precedes it. GM model can be more generally expressed as

$$a_\alpha(t + T) = k v_\alpha^m(t) \frac{\Delta v_\alpha(t)}{\Delta x_\alpha^l(t)} \quad (3.4)$$

The key of the GM model is the specification of m and l parameters. When $m = l = 0$, the model of Chandler et al. [23] is equivalent to GM model. Several research were made in order to find the optimal values of parameters m and l . The readers is referred to [13] for a historical review.

Intelligent Driver Model (IDM) IDM [147] is a continuous-time car following model for traffic simulation of freeway and urban area. IDM is formulated as an ordinary differential equation and, consequently space and time are treated as continuous variables. IDM is characterized by an acceleration function $\dot{v} := dv/dt$ that depends on the actual speed $v(t)$, gap $s(t)$ and velocity difference $\Delta v(t)$ to the leading vehicle as outlined by Figure 3.2. The IDM acceleration of vehicle α is given by Eq. 3.5.

$$\dot{v}_\alpha = \frac{dv_\alpha}{dt} = a \left[1 - \left(\frac{v_\alpha}{v_0} \right)^\delta - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha} \right)^2 \right] \quad (3.5)$$

with $s^*(v_\alpha, \Delta v_\alpha) = s_0 + v_\alpha T + \frac{v_\alpha \Delta v_\alpha}{2\sqrt{ab}}$.

In Eq. 3.5, v_0 is the desired velocity. s_0 is the minimum space (a minimum desired net distance). T is the desired time headway (the minimum possible time to the vehicle in front). a is the maximum vehicle acceleration and b is the comfortable braking deceleration.

The IDM acceleration of vehicle α can be separated into two terms: a free road term and interaction term. The free road term given by:

$$\dot{v}_\alpha^{free} = a(1 - (v_\alpha/v_0)^\delta) \quad (3.6)$$

The interaction term is given by:

$$\dot{v}_\alpha^{int} = -a(s^*(v_\alpha, \Delta v_\alpha)/s_\alpha)^2 \quad (3.7)$$

Optimal Velocity Model (OVM) This approach considers generally the difference between the driver's optimum desired velocity and the current velocity of the vehicle as a stimulus for driver's actions. The idea of OVM is based on Newell [107] and was developed by Bando et al. [6]. The mathematical formula of OVM is given by Eq. 3.8

$$a_\alpha(t) = k[V(\Delta x_\alpha(t)) - v_\alpha(t)] \quad (3.8)$$

where $k \in \mathbb{R}$ and $k > 0$ is the constant sensitivity coefficient. $V(\Delta x_\alpha(t))$ is the optimal velocity function defined as follows:

$$V(\Delta x_\alpha(t)) = 0.5v_{max}[\tanh(\Delta x_\alpha(t) - h_c) + \tanh(h_c)] \quad (3.9)$$

where v_{max} is the maximal speed of the vehicle, h_c is the safe distance, $\tanh(\cdot)$ is the hyperbolic tangent function.

Safe-Distance Models Safe-distance or collision avoidance models try to describe the dynamic of the only vehicle in relation to its predecessor, in order to respect a certain distance of safety. This model assumes the following minimum interdistance rule of Pipes [116]: “a good rule for following another vehicle at a safe distance is to allow yourself at least the length of a car between you and the vehicle ahead for every ten miles an hour (16.1 km/h) of speed at which you are traveling”.

The model of Kometani and Sasaki [71] is the first formulation based on safe following distance using physical motion equations. In this model, collision will be unavoidable

when the leading vehicle acts unpredictably and the space headway in front of the subject vehicle is shorter than the safe-distance. The development of this model is based on the use of simple Newtonian equations of motion. The model of Kometani and Sasaki [71] specifies that the minimum interdistance to avoid collision is:

$$\Delta x(t - T) = \vartheta v_{\alpha-1}^2(t - T) + \rho_l v_{\alpha}^2(t) + \rho v_{\alpha}(t) \theta_0 \quad (3.10)$$

where $\vartheta, \rho_l, \theta_0 \in \mathbb{R}$ are the constant coefficients determined by calibration. Collision avoidance models work well on describing the propagation of disturbances.

The works of Gipps [57] have completed this initial approach by incorporating several mitigating factors that the earlier formulation neglected. The model of Gipps [57] based on collision avoidance comprises two constraints for the follower's (subject's) velocity [13]:

- the speed of vehicle α should not exceed from its desired speed. The free acceleration of vehicle α should first increase with speed as engine torque increases and then decrease to zero as the vehicle approaches the desired speed;
- the following drivers must be sure that their vehicle will stop safely if the leading vehicle brakes suddenly. The previous collision avoidance models didn't contain any margin for error. The author introduced a safety margin by proposing that the driver makes allowance for a possible additional delay before reacting to vehicle ahead.

Fuzzy Logic Models The fuzzy-logic model is a car-following model using artificial intelligence. In fact, vehicle behavior is the behavior of human. Therefore, a correct description of the characteristics of human have a great importance to the effectiveness of the model. In fact, the logic thought of human being is cursory and qualitative, and consequently, the delivery and the receipt of information is not precise. Hence, fuzzy logic concept fits more on the observation, understanding, thinking and decision-making process of human. In the fuzzy logic model, human is abstracted as a fuzzy controller, whose inputs are the status messages of the preceding cars and output is the decision made through a series of thinking [77].

3.3.1.2/ LANE CHANGE MODEL

Drivers want to drive at their speed. This desire can be prevent by the leading vehicle. A driver can either adapt his speed depending on the vehicle ahead or change lane if possible. Lane change models are used to model the lateral motion of vehicles.

The lane change model is a decision model tending to approximate the behavior of the driver in the following manner: each time a vehicle has to be updated, the following question is asked: Is it needed or desirable to change lanes? The answer to the previous question will depend on the distance to the next turning and the traffic conditions in the current lane. The traffic conditions are measured in terms of velocity and queue lengths. When a driver is moving slower than he wishes, he tries to overtake the vehicle ahead. On the other hand, when he is traveling fast enough, he tends to go back into the slower lane.

3.3.2/ MESOSCOPIC MODELS

Mesoscopic modeling of the dynamics of traffic flow usually consists of a simplification that while - capturing the essentials of the dynamics – is less demanding of data and mesoscopic models are computationally more efficient than microscopic models [64]. There are two main approaches for mesoscopic traffic simulation available in literature: those in which flow dynamics are determined by simplified dynamics of individual vehicles, such as MEZZO [16] and those in which individual vehicles are not taken into account and vehicles are packed in packages or platoons (a platoon can be composed by one vehicle) that move along links as CONTRAM [76]. Another major difference between mesoscopic approaches is time management. Some approaches rely on synchronous timing while other approaches are asynchronous or event-based.

3.3.3/ MACROSCOPIC MODELS

Macroscopic models of traffic are based on a hydrodynamic analogy, i.e. a well-established mathematical basis. Macroscopic level exhibits an aggregated point of view. Traffic flow is therefore regarded as a particular fluid process whose state is characterized by aggregate macroscopic variables. Some macroscopic models involves three variables those are:

- **volume** $q(x, t)$: volume $q(x, t)$ (also referred as intensity or flow) is defined by the average number of vehicles that pass a cross-section during a unit of time t .
- **density** $k(x, t)$: density $k(x, t)$ (named also concentration) is defined by the number of vehicles per distance unit.
- **speed** $u(x, t)$: corresponding to instantaneous mean speed or space-mean speed.

One of the most common macroscopic model used in literature which is also one of the first models in road traffic modeling is the model developed simultaneously by Lighthill,

Whitham and Richards [80, 118]. This model is commonly known as the LWR model. LWR model involves the three previously described variables.

The main equation formally representing macroscopic model is the conservation equation presented by Eq. 3.11.

$$\frac{\delta q(x, t)}{\delta x} + \frac{\delta k(x, t)}{\delta t} = 0 \quad (3.11)$$

Similar to the continuity equation in hydrodynamics, Eq. 3.11 formally represents the assumption that, between two counting stations in a motorway section without entrances and exits, the number of vehicles is conserved. The conservation equation is complemented by Eq. 3.12 that is the definition of speed.

$$q(x, t) = k(x, t)u(x, t) \quad (3.12)$$

The third equation is fundamental diagram presented by Eq. 3.13. This equation assumed that traffic flow is always in equilibrium, and it passes from one state of equilibrium to another.

$$u(x, t) = u_e(k(x, t)) \quad (3.13)$$

3.3.4/ BENEFITS AND DRAWBACKS OF MONOLEVEL TRAFFIC MODELS

Microscopic, mesoscopic and macroscopic models of traffic represent traffic flow according to a specific perspective. The following presents the benefits and drawbacks of each level of detail.

3.3.4.1/ BENEFITS AND DRAWBACKS OF MICROSCOPIC MODELS

Microscopic models have the advantages to be the most accurate level of detail and the most close to the real behavior of the drivers. Microscopic models can therefore simulate a traffic scenario realistically.

However, the high accuracy of microscopic models leads to the need of high computational resource especially in large-scale networks [84]. Another drawback of some microscopic models is that they assume continuous optimization of speed. However, psychological elements tend to prove that a driver does not necessarily increase his speed even if his predecessor increases his own speed [123, 64]. Another drawback is that, some microscopic models (car-following models) seem to be usable only under conditions of heavy traffic because if the inter-vehicle distance is large enough, there is no

more interactions between vehicles and each vehicle rolls at its desired speed [158]. Furthermore, microscopic models used several variables for traffic simulation, and therefore microscopic models are not easy to calibrate [78, 64].

3.3.4.2/ BENEFITS AND DRAWBACKS OF MESOSCOPIC MODELS

As presented by Figure 3.1, on the page 33, mesoscopic models are intermediary between microscopic models and macroscopic models. Mesoscopic models could be thought of as simplified micro-simulators, offering acceptably accurate outputs but requiring much less effort in terms of computation time. Mesoscopic models combine simplified flow dynamics with explicit treatment of interrupted flows at intersections and allow modeling of large networks with high computational efficiency [146]. Furthermore mesoscopic models is less demand to calibrate than microscopic models.

However mesoscopic models exhibit coarse behavior because the positions and behavior of vehicles are approximated. The loss of realism implied by mesoscopic models make it necessary to emulate detailed outputs; for instance, detector measurements or instantaneous emissions [146]. Some outputs, such as the exact location of jam or the number of start-stops within a section elude even the most detailed mesoscopic simulators.

3.3.4.3/ BENEFITS AND DRAWBACKS OF MACROSCOPIC MODELS

Macroscopic models are the most easy to calibrate between the different representations. In fact, macroscopic models consider several partial derivative equations composed of a few variables, which describe the whole behavior of traffic flow. Another benefit of macroscopic models is that they allow to make numerical simulations on large portion. In fact, macroscopic models is the significantly lower computational costs due to lower complexity.

In contrary, due to the coarsest behavior exhibited (only the flow of vehicles is considered), macroscopic models are unable to represent a phenomena like change lane by a driver. Moreover the management of the destination of drivers in macroscopic models is a challenge.

3.3.5/ SUMMARY OF MONOLEVEL MODEL OF TRAFFIC

Macro, meso, micro models differentiate through the time and space scales. Each of them has its own advantages and drawbacks and therefore no one representation is the best. The application case is one of the main factor leading to choose either micro, meso or macro level. Generally in literature, macroscopic models are used in modeling

highway while microscopic models are used in modeling urban area and road junction. Table 3.1 summarizes the advantages, drawbacks and common application case of each representation.

	<i>Advantages</i>	<i>Drawbacks</i>	<i>Common application case</i>
Microscopic models	Most accurate and close to real traffic scenario	do not scale; difficulty of calibration	Urban area, highway, crossroad
Mesoscopic models	Scale, less demand to calibrate	Coarse behavior	Urban area, highway, large-scale networks
Macroscopic models	scale; easiest calibration	Coarsest behavior	Highway

Table 3.1: Advantages and drawbacks of traffic models

According to Mammar et al. [84], macroscopic and microscopic models are not well suited for large-scale traffic. To model and simulate large-scale traffic, mesoscopic models seems to be one of the suitable solution [16]. However, detection of the exact location of congestion (which is one of the main needs in traffic simulation) seems to be a challenge with models exhibiting coarse behavior like mesoscopic models [10].

In the 2000s, another approach combining several levels of detail has emerged [84, 17]. This approach is named multilevel models of traffic. Let's remind that, this thesis is interested by the multilevel modeling and simulation of large-scale complex system with spatial environment and that road traffic is the application case of this thesis.

3.4/ MULTILEVEL MODELS OF TRAFFIC

Multilevel models (also named hybrid models) of traffic are such models that integrates several levels of detail (at least two) in the same model. Since the levels of detail combined do not have the same time and space scale, the issue of transition between these representations arise. Multilevel model of traffic must therefore satisfies [11]:

- (i) compatibility: the representations integrated must be compatibles,
- (ii) conservation: this condition stipulates that the number of vehicles at the entry of the section must be equal to that of the exit. This ensures the non-deterioration of the information.

In order to satisfy these constraints, the multilevel model has to bring out a methodology to migrate from one representation to another representation. Literature provides two main

families of multilevel models of traffic those are static and dynamic multilevel models.

3.4.1/ STATIC MULTILEVEL MODELS OF TRAFFIC

Among the category of static multilevel models of traffic, several models have been proposed in literature. In the following the thesis presents some of them.

3.4.1.1/ THE MODEL OF MAMMAR ET AL. [84]

Mammar et al. [84] integrated two representations in the same model. These representations are macroscopic and microscopic representation. In one hand, the macroscopic model used is ARZ model [5, 159]. ARZ is a second order macroscopic model. In the other hand, the microscopic model used is tracking model. Tracking model models are based on hypotheses that the reaction of driver depends on the collected information from the environment. The tracking principle selected by the authors is close to ARZ model.

Since micro and macro models do not have the same features variables, as stated before, the question of transitions between micro and macro models arise. To solve this issue, the authors propose a coupling scheme presented in Figure 3.3. The coupling schema based on transition cells considers two type of transitions: a shift from macro to micro model and a shift from micro to macro model. To validate their approach, the authors studied a real world scenario: the propagation of a congestion to downstream and the propagation of congestion to upstream.

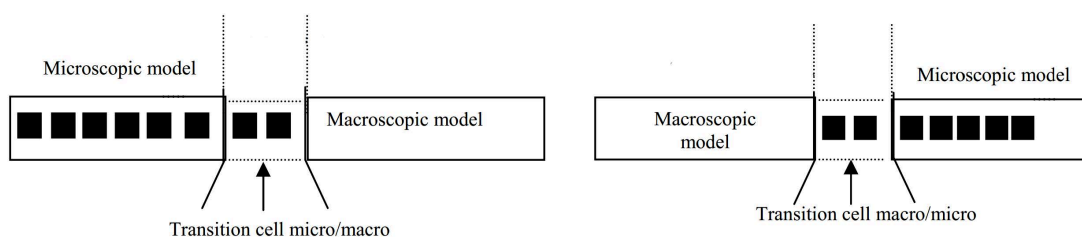


Figure 3.3: Coupling schema proposed by Mammar et al. [84]

3.4.1.2/ THE MODEL OF SAID EL HMAM ET AL. [126]

The goal of the authors is to couple two traffic representations with different scale levels. The representations coupled were microscopic and macroscopic representation. The microscopic level is based on the agent paradigm (more detail on chapter 3 and the macroscopic level is based on the first order LWR model [80]. The objective of the authors was the development of a coupling schema allowing flexibility. To this end, the authors

proposed a coupling schema presented in Figure 3.4. The coupling schema considers macro-micro and micro-macro interfaces. The macro-micro interface translates the transition from a continuous state to a granular one. Micro-macro interface used an agent placed at the macro-micro interface of the two part of the section named agent upstream whose purpose is to calculates the density of upstream transition cell used to generate a number of vehicles according to the flow.

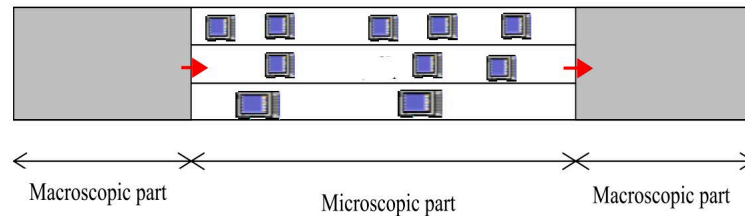


Figure 3.4: Hybrid model principle proposed by said EL Hmam et al. [126]

3.4.1.3/ THE MODEL OF MOUTARI AND RASCLE [99]

Moutari and Rascle [99] proposed a discrete multilevel model for vehicular traffic flow. The proposal used both macroscopic and microscopic level. The macroscopic model is based on the Aw–Rascle (AR) model [5] while the microscopic model is based on one GM stimulus-response car-following model. The authors proposed an hybridization scheme allowing relationship between representations outlined by Figure 3.5. The hybridization scheme is based on the Lagrangian discretization of both the macro and the micro models, coupled through Lagrangian interfaces periodically refreshed in order to always contain a fixed Eulerian region near an obstacle. The authors present several numerical examples showing that the waves produced in either region nicely propagate through the other region.

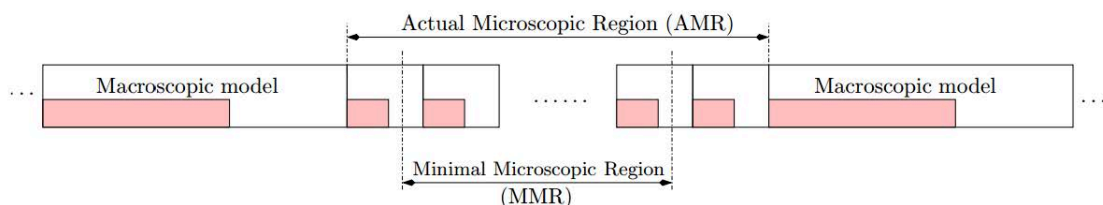


Figure 3.5: Hybrid Langrangian Model proposed by Moutari and Rascle [99]

3.4.1.4/ THE MODEL OF BURGHOUT ET AL. [18]

The authors combine two representations in the same model for a hybrid simulation of traffic flow. These representations are microscopic and mesoscopic. In order to make these representations compatible, the authors proposed an integration framework presented in Figure 3.6. The authors define and implement conditions for consistent interfaces between the meso and micro simulation components. In particular, three main consistency issues are highlighted: formation of a consistent network representation from the meso and micro sub-networks, consistency in route choice behavior and consistency of traffic dynamics at meso-micro boundaries. The integration framework proposed satisfies the stated requirements. The authors validate their model by a case study. To this end, two simulation models are integrated: MITSIMLab (Mitsim) [155] and Mezzo [16].

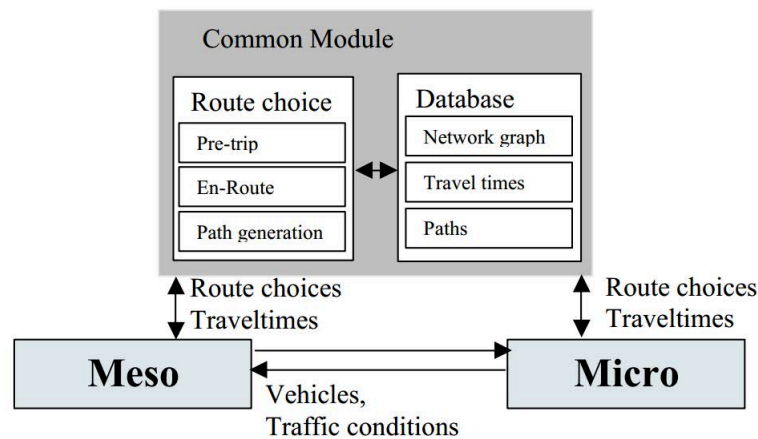


Figure 3.6: Integration architecture proposed by Burghout et al. [18]

3.4.1.5/ THE MODEL OF BOURREL AND LESORT [11]

Bourrel and Lesort [11] proposed a mixed micro macro representations of traffic flow. The authors proposed some theoretical frameworks needed for the construction and the validation of a hybrid model. The two traffic models used are based on the same LWR behavioral rules, and they used shock waves as a common information. LWR model is based on a discretization of the acceleration fans in a finite number of accelerating shock waves. The interfaces between the two models receive this information from both sides and transmit it. Figure 3.7 presents the hybridization principle proposed. The authors computed their model in two simple cases those are stationary situation and propagation of a shock wave, and they stated that shock waves propagate correctly.

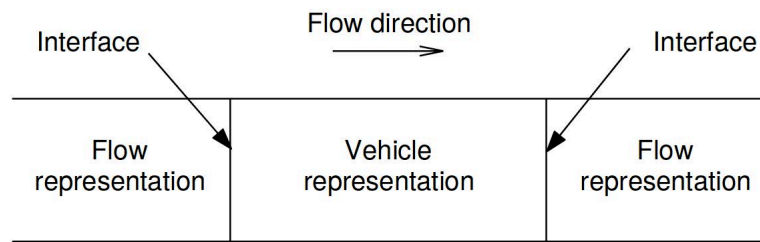


Figure 3.7: Hybridization model proposed by Bourrel and Lesort [11]

3.4.1.6/ SUMMARY OF STATIC MULTILEVEL MODELS OF TRAFFIC

Most of the static multilevel models of traffic have the following principle:

- (i) divide the road network in two sections,
- (ii) choose the two models to be interfaced,
- (iii) assign each model to be interfaced to a section of road network,
- (iv) manage transitions at the border between road sections.

The models presented by Figures 3.3, 3.4, 3.5, 3.6, 3.7 follow this principle. The various static multilevel models available in literature mainly differ on the choice of the models to be interfaced [84]. Table 3.2 summarizes these models.

Static multilevel models of traffic have several drawbacks:

- Generally these models select only two levels of detail to be combined either micro–meso either micro–macro or meso–macro. Since a complex system can be modeled according to several points of view: micro, meso or macro, we argue that it can be interesting to combine into a same model more than two levels of detail.
- Decomposition of road network in sections is made a priori i.e. by an expert. In fact, the success of a static multilevel model of traffic depends on the quality of the decomposition of road network in sections and the suitable choice of the representation associated to each section of road. Decomposition of road network in sections and the choice of the suitable representation associated to each section of road are therefore a critical activity.
- Lack of flexibility and reusability. Bourrel and Lesort [11], Mammar et al. [84], said EL Hmam et al. [126] have proposed static multilevel models of traffic interfacing micro and macro. However, these models are completely independents. It can be interesting to have reusable multilevel models of traffic.

	<i>Methodology</i>	<i>Coupling scheme model</i>	<i>Highlighted Models</i>	<i>Connection</i>	<i>Level of detail</i>
Magne et al. [82]	Decomposition of road, Management of the virtual cells	Aggregation / disaggregation, Progressive transition of information (not punctual)	SITRA-B+, SIMRES	Fixed a priori	Micro, macro
Poschinger et al. [117]	Decomposition of road, Management of the transition zone (at the border)	Aggregation / disaggregation; Progressive transition of information (not punctual)	IDM, Payne	Fixed à priori	Micro, macro
Bourrel and Lesort [11]	Decomposition of road, Management of the transition zone (at the border)	Aggregation / disaggregation; Transmission of information to interfaces by phantom vehicles	Optimal velocity, LWR	Fixed à priori	Micro, macro
Burghout [16]	Mesoscopic virtual links and microscopic virtual links, consistency in network representation at boundary	Integration architecture based on common module	Mitsim, Mezzo	Fixed à priori	Micro, meso
Mammar et al. [84]	Decomposition of long motorway; space discretization	Transition cell; management of equilibrium, out of equilibrium flow	Tracking model, ARZ	Fixed a priori	Micro, macro
Espie et al. [38]	Decomposition of road network; virtual transition zone at each interface	Founded on progressive information transmission	ARCHISM, SSMT	Fixed a priori	Micro, macro
said EL Hmam et al. [126]	Decomposition of highway in two parts. Management of the transition zone	Management by Agent upstream and agent downstream	Agent based model, Payne	Fixed a priori	Micro, macro

Table 3.2: Some static multilevel models of road traffic flow [143]

- These models are statics. In fact, once a representation and its corresponding model has been associated to a section of the road, this representation cannot evolve during runtime. However, to be able to observe congestion formation or to find the exact location of a jam in a macro section, a dynamic hybrid modeling approach is needed [10].

The previous drawbacks raise up the necessity of dynamic multilevel models of traffic. Let's remind that, the goal of this thesis is to build a dynamic multilevel model of large-scale complex system with road traffic as an application case.

3.4.2/ DYNAMIC MULTILEVEL MODELS OF TRAFFIC

In contrary to static multilevel models of traffic flow, dynamic multilevel models of traffic allow to migrate dynamically between representations on the same road section. There are few works on dynamic multilevel models of traffic flow available in literature [10, 3]. Tchappi et al. [143] identified in their state-of-the art two works available in literature which propose to migrate dynamically and automatically between levels of detail: the model of Sewall et al. [129] and SIMILAR/JAMFREE [3, 10].

3.4.2.1/ THE MODEL OF SEWALL ET AL. [129]

Sewall et al. [129] proposed a flexible real-time algorithm for modeling large-scale traffic using a hybrid model of both continuum and agent-based methods. In this model, the road network is divided into multiple disjoint regions that cover the domain. Each region is governed by either continuum simulation or agent-based simulation. In this model, regions are not necessarily connected nor static i.e. it's possible to pick either technique to govern a given part of the traffic network based on observations, application requirements, a user's field of view etc. In fact, it is possible to adaptively change the shape of and the simulation method in a region as needed to observe certain phenomena, meet performance requirements, or to respond to user input. Migrating between the two simulation models can be dynamic and automatic based on specified governing criteria, similar to real-time graphical rendering using geometric levels of detail. The authors proposed a methodology to convert discrete vehicles from agent-based simulation lanes into the aggregate format needed for continuum simulation. The authors proposed also a methodology to use the distribution of density in continuum lanes to introduce discrete vehicles for agent-based simulation.

3.4.2.2/ SIMILAR/JAM-FREE

Abouaïssa et al. [3], Bouha et al. [10] proposed SIMILAR/JAM-FREE to deal with dynamic multilevel model of road traffic. SIMILAR (SIMulations with Multi-Level Agents and Reactions) previously called IRM4MLS [140, 139] is a framework based on influence-reaction and agent-based knowledge representation to design simulations. JAM-FREE is a multi-level agent-based traffic simulator. In JAM-FREE, the road network is dynamically divided into subsets called clusters by authors. Road traffic is simulated on each cluster using either microscopic models or macroscopic models. The goal of their hybrid model was to dynamically change the traffic representation of a portion of the road network: transition from a microscopic to a macroscopic representation (when the CPU is overloaded, in order to reduce its load) and from a macroscopic to a microscopic representation to find out why a traffic jam has appeared.

3.4.2.3/ SUMMARY OF DYNAMIC MULTILEVEL MODELS OF TRAFFIC

The main added value of dynamic multilevel models of traffic is the ability to migrate between representations on the same section of road network. In these models a same section of road network can be simulated at several levels of detail. Table 3.3 summarizes dynamic multilevel models of traffic.

As outlined by Table 3.3, literature lacks of dynamic multilevel models of traffic flow.

	<i>Methodology</i>	<i>Coupling scheme model</i>	<i>Highlighted Models</i>	<i>Connection</i>	<i>Level of detail</i>
Sewall et al. [129]	Detailed road network; lane based representation; arcs road	Aggregation / disaggregation of vehicles; Flux capacitors, vehicle instantiation based on Poisson process	Agent based model, ARZ	Fixed a priori	Micro, macro
SIMILAR / JAMFREE [3]	Semantic decomposition of road network in autonomous cluster	Aggregation and disaggregation of traffic variables; Formal multi-level agent-based meta-model	IDM, METANET	Fixed a priori	Micro, macro

Table 3.3: Some dynamic multilevel models of road traffic flow [143]

Moreover, among the existing dynamic multilevel models of traffic, the work of Sewall et al. [129] focuses on visualization of data rather than accurate simulation of traffic. SIMILAR/JAM-FREE on the other hand is little described. Furthermore, these models focus only on two levels of detail: microscopic and macroscopic. However, microscopic and macroscopic are too far away representations [106]. It can be interesting to build a dynamic multilevel model of traffic taking into account microscopic, mesoscopic, macroscopic representation. This is the goal of this thesis.

3.5/ CONCLUSION

This chapter presents road traffic models. In fact, monolevel models of traffic were presented. Monolevel models of traffic represent traffic according to only one perspective. Depending on the application case, the designer can focus either on microscopic models, either on mesoscopic models or either or macroscopic models. Figure 3.8 presents a summary of monolevel models of traffic. However, as highlighted in this thesis, traffic is a large-scale complex system which exhibit a behavior from several perspectives. Thus, to enable the modeling and simulation of traffic systems from several perspectives, multilevel models are one of the appropriate solutions [84]. In fact, multilevel models of traffic can represent traffic according to several perspectives (at least two). Multilevel models of traffic have the advantage of combining the advantages of micro, meso or macro representation.

The first authors who were interested by multilevel models of traffic have proposed some static multilevel models of traffic. Although interesting, static multilevel models of traffic have several drawbacks such as the lack of reusability, the need of an expert for road decomposition etc. In order to enhance these models, dynamic multilevel models were proposed. Dynamic multilevel models of traffic allow to represent traffic from several perspectives and allow to dynamically migrate between representations during simulation. Figure 3.9 presents a summary of multilevel models of traffic.

Few research works were interested by the dynamic multilevel modeling and simulation of traffic. This thesis outlines the work of Sewall et al. [129] and SIMILAR/JAM-FREE. The few number of research works on dynamic multilevel model of traffic raises up the need of further research. To tackle this issue, it is necessary to ensure the following constraints.

- **compatibility:** the representations integrated must be compatibles,
- **conservation:** the number of vehicles at the entry of the section must be equal to that of the exit.

Due to the important number of entities involved in large-scale complex systems, the high number of interactions between these entities, a suitable approach is needed for their study. Holonic Multi-Agent System is an interesting and flexible solution allowing to model dynamically large-scale complex system with spatial environment such as large-scale traffic. The holonic multiagent system paradigm is presented in the next chapter of this thesis.

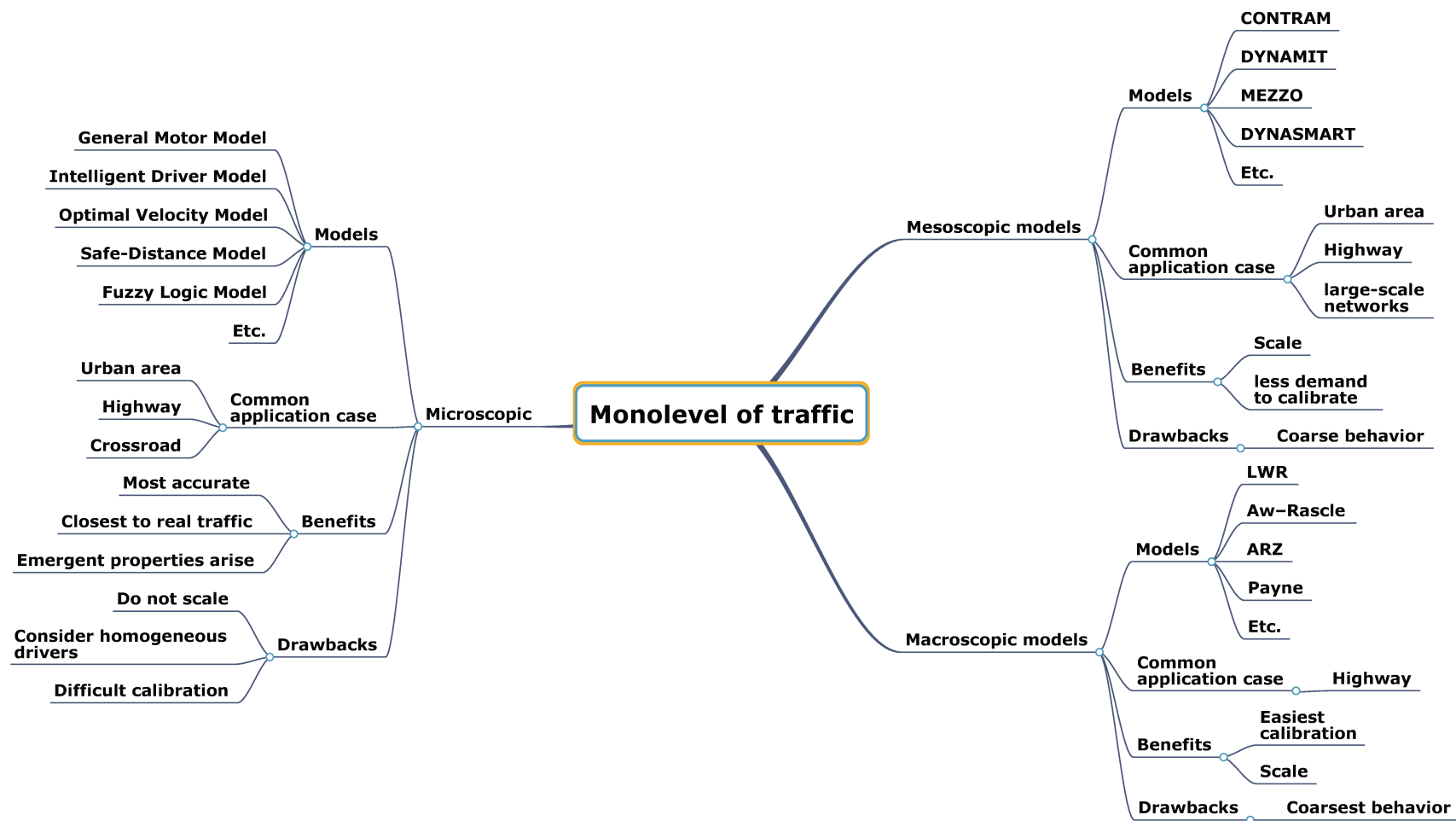


Figure 3.8: Summary of monolevel models of traffic

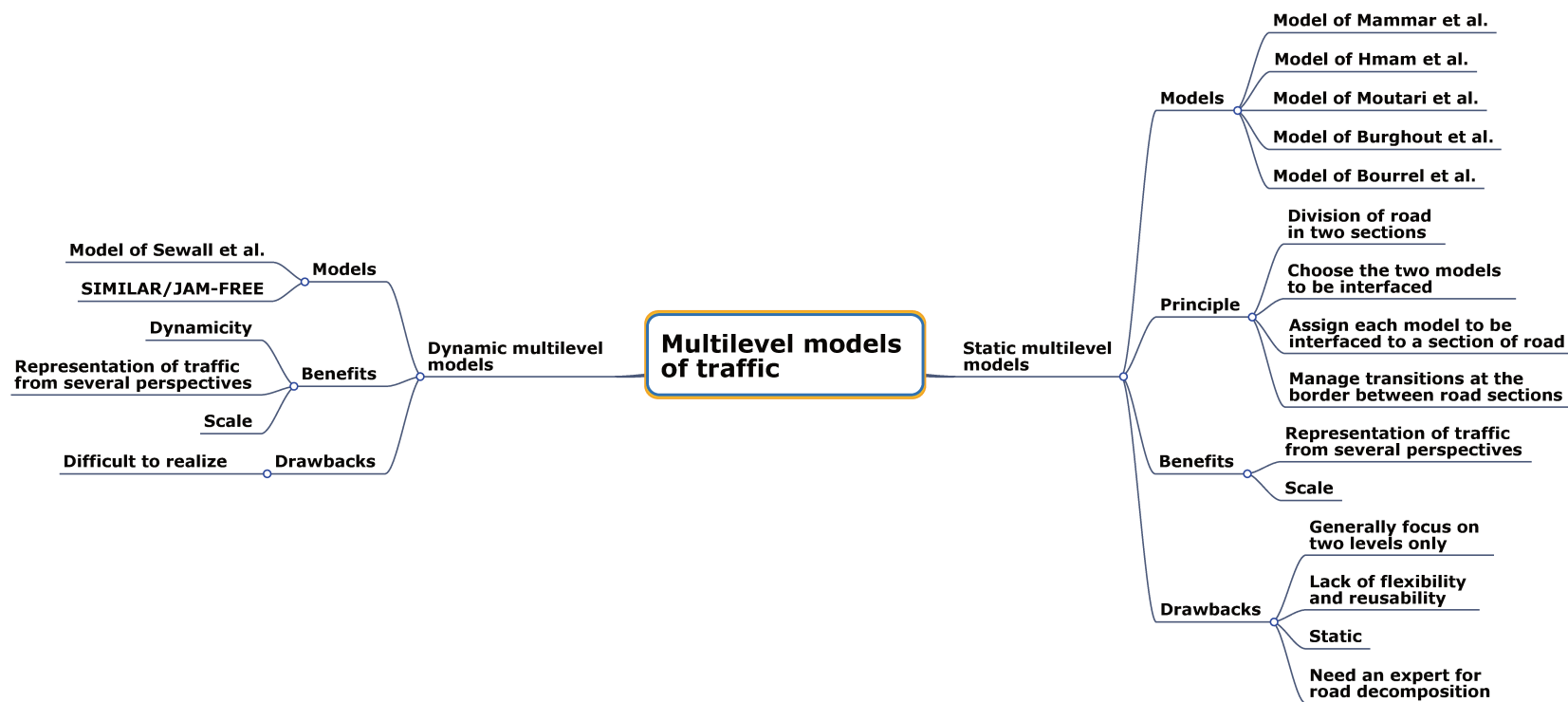


Figure 3.9: Summary of multilevel models of traffic

HOLONIC MULTI-AGENT SYSTEMS FOR MODELING AND SIMULATION OF LARGE-SCALE COMPLEX SYSTEMS

4.1/ INTRODUCTION

The previous chapter highlights that large-scale complex systems with spatial environment such as road traffic systems exhibit a behavior at several levels of detail (micro, meso and macro). Let's remind that a level of detail (or an abstraction level or a level of observation) refers all to a perspective of the system source as asserted by Morvan [96]. Let's remind also that multilevel modeling and simulation is an interesting approach to deal with systems exhibiting hierarchical behavior.

This chapter presents the Holonic Multi-Agent System (HMAS): a suitable paradigm allowing the multilevel modeling and simulation of systems exhibiting a hierarchical behavior. In fact, HMAS is one of the suitable paradigms allowing modeling and simulation of large-scale complex systems at several levels of detail. HMAS have been successfully applied to a wide range of applications. For instance, this manuscript can mention the works done in adaptive mesh problem [121], transportation [50, 143, 60, 122, 144], distributed sensor management [8], supply chain management [86], health organisations [150], complex software systems [93], biological network simulation [130] to name a few.

The goal of this chapter is to present HMAS. To this end, the first section of this chapter is dedicated to Multi-Agent System (MAS). In fact, HMAS is a particular type of MAS [74]. The fundamentals of MAS paradigm and the related definitions are presented. Then the fundamentals of HMAS and the related definitions are also detailed. Moreover, approaches for building large-scale complex systems through HMAS paradigm are highlighted. Finally, the benefits and drawbacks of HMAS paradigm are discussed.

4.2/ MULTI-AGENT SYSTEMS

This section is structured as follows: Section 4.2.1 defines and presents the main properties of Multi-Agent System (MAS) and Section 4.2.2 outlines some drawbacks of MAS paradigm.

4.2.1/ FUNDAMENTALS OF MAS

Nowadays, the development of computing in terms of the increasing power of computers, the evolution of networks, the increase of the quantity of information to be processed and stored have led to complex application needs. MAS paradigm is one of the suitable solutions dealing with distributed complex systems [42, 41, 66]. In fact, MAS can reproduce complex spatial, temporal, organizational, social, and cognitive systems [148, 96]. MAS paradigm offers therefore the robust solutions that can adapt itself in unpredictable environments. MAS is an organized set of interacting entities. Entities of MAS are called “agents”.

4.2.1.1/ DEFINITION OF AGENT CONCEPT

There are several definitions of the concept of agent in literature. This thesis presents some of them.

Definition 17: Agent according to Russell and Norvig [125]

An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors

Definition 17 is one of the most widely used definitions for the concept of agent. In this definition, the main actions of agents those are perceive environment and act on it are highlighted.

Definition 18: Agent according to Jennings and Wooldridge [67]

An agent is a computer system, situated in some environment, that is capable of flexible autonomous action in order to meet its design objectives

Jennings and Wooldridge [67], in Definition 18 highlight three key properties of an agent those are situatedness, autonomy and flexibility. More generally, the main properties of an agent are [67, 66]:

- **Autonomy:** means that the agent should have control over its own actions and internal state. The system therefore should be able to act without the direct intervention of humans or other agents.

- **Sociability:** : agents should be capable to interact (cooperation, collaboration, coordination) with other agents in order to achieve its goals or to assist other agents in their activities. Agents can have some communication skills to exchange information.
- **Situatedness:** means that the agent receives sensory input from its environment and that it can perform actions that modify the environment in someway.
- **Flexibility/Adaptability:** agent adapts its behavior according to its perception of the environment and can participate in organizations in order to better meet its goal. Agent can have the ability to learn and improve with experience.
- **Reactivity:** agents should perceive their environment and react in a timely manner to changes in their environment
- **Proactivity:** agents should do not only act in response to the environment, they should be able to adopt opportunistic and goal-oriented behavior and take the initiative,

In summary, agents are endowed with attributes, behaviors, perception and communication skills. The set of values of the attributes of an agent at a given instant constitutes the state of this agent, and the union of all the states of the agents constitutes the state of the system. A system composed by several interacting agents refer to a MAS.

4.2.1.2/ DEFINITION OF MAS

Several authors generally agree to define a MAS as a system composed of several agents which communicate and collaborate to achieve specific individual or collective goals. Following this common point of view of MAS, Ferber [40] defines a MAS as:

Definition 19: Multi-Agent System according to Ferber [40]

A MAS is a system composed by the following elements:

- An environment, E that is a space which generally has a volume.
- A set of objects, O . These objects are situated, that is to say, it is possible at a given moment to associate any object with a position in E . These objects are passive, that are they can be perceived, created, destroyed and modified by the agents.
- An assembly of agents, A , which are specific objects representing the active entities of the system.
- An assembly of relations, R , which link objects (and thus agents) to each other.
- An assembly of operations, Op , making it possible for the agents of A to perceive, produce, consume, transform, and manipulate objects from O .

Definition 19 is a general definition and depending on the cases encountered, some sets described above are zero. This definition can therefore be adapted according to the problem and the type of agents to model.

Definition 20: Multiagent System according to Jennings and Wooldridge [67]

A MAS is a system composed by several autonomous agents such that:

- Each agent has incomplete information or capabilities to solve the problem
- There is no global control on the system
- Data is distributed
- Computations are asynchronous

Jennings and Wooldridge [67] raise up the notion of problem solving and they insist on the notion of agent autonomy. The autonomously interactions of agents within the environment creates the dynamic of the system at the level of individuals (micro) and also at the collective level (macro) through emergence (the appearance of a global behavior that is not deductible from the behavior of the individuals). In fact, MAS is an organized society of agents in which a certain number of phenomena may emerge as a result of the interactions between the agents. The notion of emergence is essential in MAS, as it is one of the properties that make them so suitable for modeling complex systems.

4.2.2/ DRAWBACKS OF MAS

MAS constitutes a powerful approach for solving distributed complex problems based on the distribution of knowledge and skills across a set of autonomous entities. MAS is widely used in the modeling of complex systems [41, 42, 66, 67, 33, 34]. MAS has also several drawbacks those are:

- The perspective adopted by MAS is at the level of the individuals, and the dynamics of the system are the outcome of interactions between individuals. Therefore, at the system level, no performance guarantees seems available [96]. In other words, because MAS focuses on the interactions between individuals, there is no global conceptual design, global constraints/requirements that solution must satisfy and therefore MAS seems to face with difficulties to guarantee in advance a particular desired global behavior of the system.
- MAS does not scale easily and generally requires a high computational resources when the number of agents involved is large [10, 50, 51]. MAS is therefore faced of several difficulties for modeling and simulation of large-scale complex system.
- Most agent-based simulation platforms lack tools to reify (reification consists in considering an abstract idea as a concrete thing) complex singular emergent properties. The observation of a human often remains the most efficient way to capture multilevel pattern formation [96].

Multilevel agent-based modeling has been proposed to address some drawbacks of MAS. In fact, multilevel agent-based modeling can provide a solution to model a system exhibiting several levels of detail by making it possible to modulate the complexity of the system. Details on the multilevel agent-based modeling are provided in the following section.

4.3/ FOCUS ON MULTILEVEL AGENT BASED MODELING

One of the main approach enabling multilevel agent based modeling is the definition and implementation of metamodels, simulation engines and platforms. In fact, several metamodels and simulation engines allowing multilevel agent based modeling have been proposed in literature. They are presented below inspired by the review of Morvan [96].

DEVS (Discrete Event Systems) was proposed by Zeigler et al. [157] as a formalism to account for any kind of discrete event system. DEVS take into account proactive/reactive behavior (an agent reacts to incoming events if it wants to, and behaves proactively, regardless of the complexity of its internal architecture behavior). There are several extensions available for DEVS metamodel presented by Müller [101].

GEAMAS (GEneric Architecture for MultiAgent Simulation) [87, 88] is a framework integrating the three main levels of detail: micro, meso (called medium level by the authors) and macro level. The micro and macro levels represent the agent and system views respectively, while the meso level represents an aggregation of agents in a specific context. Each level is independent and executes processes asynchronously. To manage transition between individual and collective level, the authors introduced the mechanism of decomposition and recomposition. Decomposition allows transferring information to lower level, until recomposition allows transferring information to higher level. GEAMAS-NG [28] is a newer version of the framework providing tools for detection and reification of emergent phenomena

tMans¹ (the Multi-scale Agent-based Network System) [128] is a multi-scale agent-based framework in order to understand and model multi-scale interdependent behavioral phenomena. This project seems to be forsaken.

ML-DEVS (Multi-Level-DEVS) [141, 149] is an extension of DEVS supporting an explicit description of macroscopic and microscopic level. In this framework, information at macroscopic level can be accessed from microscopic level and vice-versa. Moreover, microscopic models can be synchronously activated by the macroscopic model and also the microscopic models can trigger the dynamics at macroscopic level. A combination of several methods (value coupling, synchronous activations, variable ports, etc.) is used by the authors to link abstraction levels.

SPARK² (Simple Platform for Agent-based Representation of Knowledge) [137] is a framework for multiscale agent-based modeling specifically designed for biomedical model development.

Scerri et al. [127] proposed an architecture and framework allowing integration of multiple agent-based simulations into a single global simulation. The authors seek to ensure appropriate management of simulation data that is affected by agents in different modules, at the same logical time.

IRM4MLS³ (Influence Reaction Model for MultiLevel Simulation) [98, 97] is a multi-level extension based on the Influence Reaction principle [91]. In this theory, an agent produces “influences ” (e.g. individual decisions, according to their internal state and perceptions) and environment “reacts” (e.g., computes the consequences of influences) according to the state of the world.

Müller et al. [102] sought to understand the relationships between residential segregation and school segregation, resulting from the interaction between school supply and the choice of students. To this end, the authors considered three points of view: the ge-

¹<http://tmans.sourceforge.net/>

²<http://www.pitt.edu/~cirm/spark/>

³<http://www.lgi2a.univ-artois.fr/~morvan/Gildas.Morvan/IRM4MLS.html>

ographer, the sociologist and the economist. Then, for each point of view, independent conceptual agent-based models are defined. Ontological approach is used to highlight differences in disciplinary views on a common object of interest.

PADAWAN (Pattern for Accurate Design of AgentWorlds in Agent Nests) [115] is a formalism to represent multiple environments, endowed with their own spatial and temporal scales and with behavioral rules for the agents they contain. PADAWAN is a frame for the decomposition of a multi-layer complex system, whether for simulation or distributed problem solving.

GAMA⁴ (GIS & Agent-based Modeling Architecture) [142, 34] is an agent-based simulation platform. GAMA allows modelers to define spatially explicit and multi-levels models. GAMA provides a modeling language based on XML named GAML, that allows the definition of complex models integrating at the same time entities of different scales and geographical vector data.

AA4MM (Agent and Artifact for Multi-Modeling) [19, 132] sought to build and simulate the heterogeneous multi-model of a complex system from a set of pre-existing models already implemented in simulation software. Levels are reified by agents that interact through artifacts.

CRIO (Capacity - Role - Interaction - Organization) [119, 50] is a general framework for designing complex system. CRIO is based on four main interrelated concepts those are:

- **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 can interact with other roles defined in the same organization.
- **Interaction:** links two roles in a way that an action in the first role produces a reaction in the second.
- **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 MAS following an organizational perspective. Moreover, CRIO provide also a framework for modeling holonic multiagent system which is a particular type of agent-based system.

⁴<http://code.google.com/p/gama-platform/>

4.4/ HOLONIC MULTI-AGENT SYSTEM

Holonic Multi-Agent System (HMAS) is a paradigm allowing the modeling and simulation of complex system. This section presents the fundamentals of HMAS.

4.4.1/ FUNDAMENTALS DEFINITIONS

The holonic concept was developed by Koestler⁵ in 1967 to explain the evolution of biological and social systems. A biological example is given by Koestler, that is a human being made up of organs, which in turn consist of cells that can be further decomposed, and so on. None of these biological components can be understood without its sub-components or without the super-component it is part of. This example outlines the interdependence or relationship between sub-components and super-components for a human. More generally, the relationship between parts and whole is highlighted. In the same vein, Blaise Pascal⁶ highlighted also the relationship between parts and whole in his statement “I cannot conceive the whole without conceiving the parts, and I cannot conceive the parts without conceiving the whole”. The statement of Blaise Pascal leads the ways to the “holism”.

The term holism was coined by J. C. Smuts⁷ [135]. Aristotle has described the general principle of holism in these terms: “the totality is not, as it were, a mere heap, but the whole is something besides the parts”. Some others authors describe the principle of holism by the following statement : “the whole is more than the sum of its parts” [50, 53, 70]. Figure 4.1 presents a visual example of holism through the fractal (a fractal object is an object of which each element is also a fractal object) of the Sierpiński triangle. In this example the parts are triangles and the whole is also a triangle.

The idea put forward by the holonic concept follows the holism philosophy. The holonic concept therefore is based on the idea that all the properties of a given complex system cannot be determined or explained by its components (constituent elements) alone. Holonic modeling is used to model the intrinsic hierarchical nature of complex systems. Holonic modeling is based on a set of holons (Definition 21).

⁵Arthur Koestler (1905 – 1983) was a Hungarian-British author, journalist and philosopher

⁶Blaise Pascal (1623 – 1662) was a mathematician, physicist, inventor, philosopher, moralist and theologian French

⁷Jan Christiaan Smuts (1870–1950) was a South African politician and former prime minister of South Africa

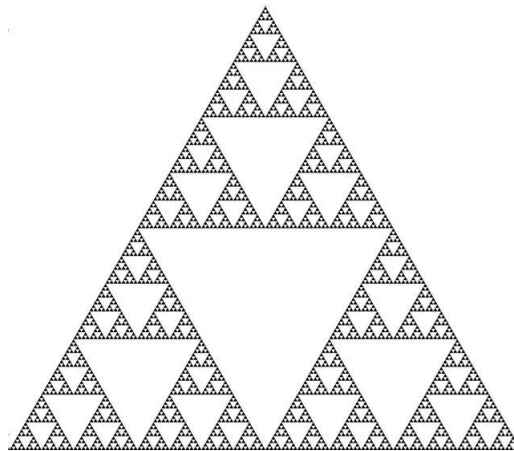


Figure 4.1: Sierpiński triangle. The triangle can be constructed from an equilateral triangle by repeated removal of triangular subsets: (1) start with an equilateral triangle; (2) subdivide it into four smaller congruent equilateral triangles and remove the central triangle; (3) repeat step (2) with each of the remaining smaller triangles infinitely.

Definition 21: Holon according to Koestler [70]

The term holon is a combination of the Greek words *holos* meaning whole and the suffix *-on* meaning part. A holon is defined as simultaneously a whole and a part of the whole, thus it can be made up of other holons, strictly meeting three conditions: being stable, having a capacity for autonomy and being able to cooperate.

A holon is the main component of a HMAS allowing to put forward the relationship between the parts and the whole. HMAS is a paradigm applying holism philosophy based on the concept of holon. More precisely, HMAS is defined as follows.

Definition 22: Holonic Multi-Agent Systems according to Gerber et al. [53]

HMAS is a recursive structure of holons.

The underlying idea of HMAS is that a number of holons can be created and coalesce to form other higher-level holons, generating thus a hierarchical system. The structure of the hierarchical system in HMAS is called holarchy (Definition 23).

Definition 23: Holarchy according to Gerber et al. [53]

The holarchy is the organizational structure of a holonic society. The holarchy is a hierarchy of self-similar holons functioning first as supra-ordered sets of their components, then as dependent and subordinate parts of higher-level control, and finally in coordination with their local environment.

Holarchy offers advantages that the monolithic design of most technical artifacts lack: it

is robust in the face of external and internal disturbances and damage, and it is efficient in their use of resources and it can adapt to environmental changes [53]. Figure 4.2 presents a holarchy with three holarchical levels (levels of detail). The entire structure of the holarchical levels is made through holonification (Definition 24).

Definition 24: Holonification according to Gaud [50]

Holonification is the process of building a holarchy, whatever the method (upward, downward, etc.) used for creating the holons and their relationships.

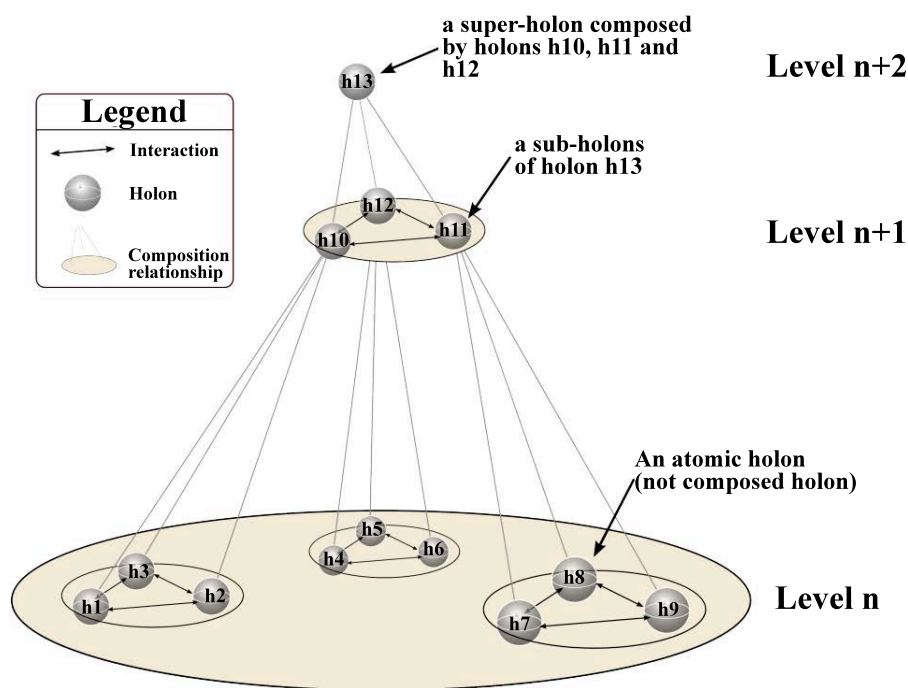


Figure 4.2: A holarchy with three holarchical levels [50].

Definition 21 gives a general definition of a holon. In addition, Definition 25, which follows the global idea of Definition 21, circumscribes the definition of the concept of holon in HMAS field.

Definition 25: Holon in HMAS according to Gerber et al. [53]

A holon in HMAS is an agent that could be composed of agents.

According to Koestler [70] and Gerber et al. [53], a holon exhibits a dual property. A holon can represent a whole and a part of a whole. This duality property brings out the notions of super-holon and sub-holon [119].

Definition 26: Super-holon according to Rodriguez [119]

A super-holon can be considered as a set of interacting holons at a given level of detail. These interactions define the structure and the overall behavior of the super-holon.

Definition 27: Sub-holon according to Rodriguez [119]

Sub-holons can be considered as holons composing a super-holon.

Definition 28: Atomic holon according to Rodriguez [119]

An atomic holon is the non-decomposable holons.

In order to understand well the HMAS paradigm, this thesis provides an example from Gaud et al. [51]. A university can be considered from a holonic point of view. University can be therefore broken down into different departments and laboratories. In the same way, a department can be broken down into a set department council, courses, etc. populated by teachers and students. The holarchy of the university is described in Figure 4.3. At the highest level (level $n + 2$) is the holon university, which in this example is composed of three sub-holons: the computer department, the mechanical department and a laboratory (level $n + 1$). At the lowest level are atomic holons lecturers, students

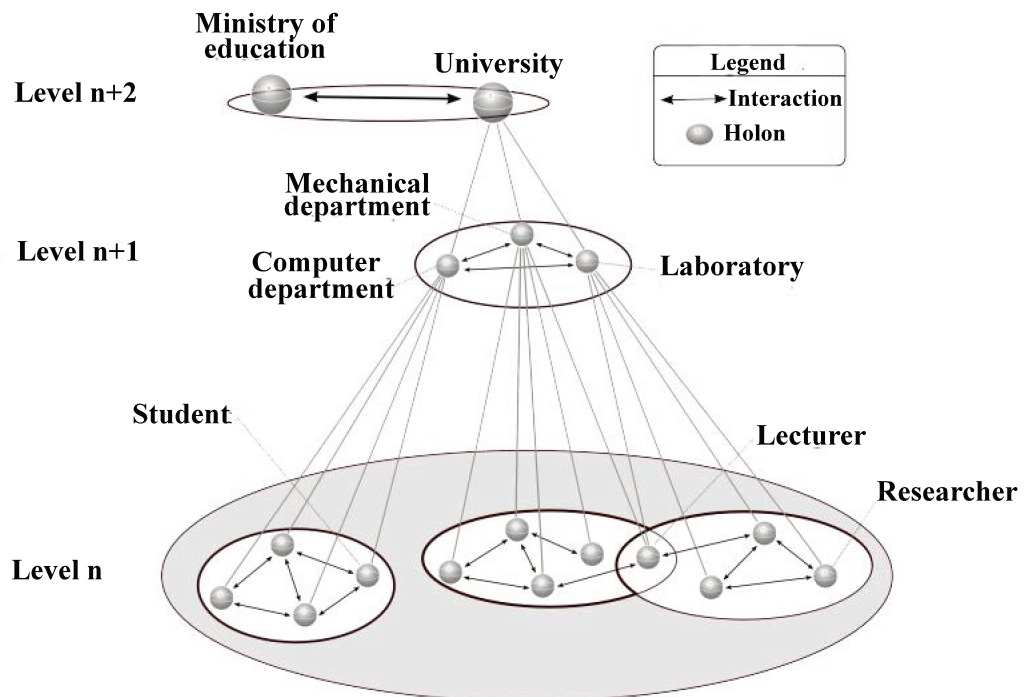


Figure 4.3: Example of the holonic structure of a university [50]

and researchers (level n). In this example, university is designed by a HMAS. Holarchy represents the structure of the HMAS i.e. the composed/composition of holons from the lowest level to the highest level. Holonification is the process of building the holarchy i.e. the university decomposition process.

4.4.2/ COMMUNICATION IN HOLONIC MULTI-AGENT SYSTEM

Social capacity is a recognized property of holons [53, 50, 120]. As shown on Figure 4.2 page 62, in holarchy, holons lie at different levels of detail. The organizational structure of a holonic society allows therefore two types of communications or interactions [119]:

- intra-level communication (cf. Figure 4.4, (left side)) : when holons communicating with holons at the same level of detail. This kind of communication is sometimes referred as horizontal communication.
- inter-level communication (cf. Figure 4.4, (right side)): When holons of two different levels of the holarchy communicate. This kind of communication is sometimes referred as vertical communication.

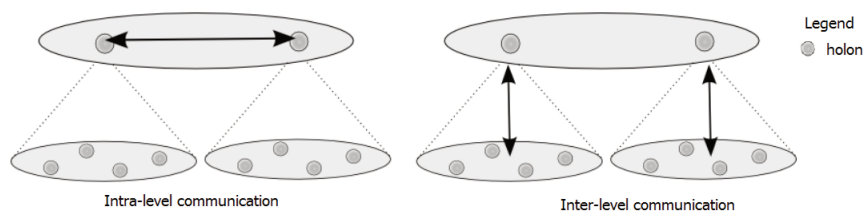


Figure 4.4: Intra-level and inter-level communication [119]

4.4.3/ COMPARISON BETWEEN MAS AND HMAS

Having presented the fundamentals of both MAS and HMAS paradigms, this section summarises them by a cross comparison.

AGENT VS. HOLON

One recurring question arises when talking about HMAS and MAS that is: what is the difference between holons and agents? or how are holons linked to agents? Several answers to this question can be given depending on how the holons are perceived. Giret and Botti [58] have proposed a general comparison between holons and agents. By

definition, holons are composed of others holons referred in this work respectively as super- and sub-holons, while agents are generally not composed of other agents i.e. agents are generally atomic entities. Table 4.1 presents the main differences between holons and agents in the general case.

	<i>Agents</i>	<i>Holons</i>
Composition	Generally atomic	Composed
Organization	Heterarchy, Hierarchy(sometimes)	Holarchy
Autonomy	Yes	Yes
Reactivity	Yes	Yes
Pro-activity	Yes	Yes
Social ability	Yes	Yes
Learning	Yes	Yes
Rationality	Yes	Yes
Recursiveness	Generally no recursive architecture but some techniques could be used to simulate different recursive levels	Yes

Table 4.1: Main differences between Agents and Holons based on [58]

MAS vs. HMAS

After presenting the differences between holon and agent, it can be interesting to present also differences between MAS and HMAS. In fact, HMAS is an extension of agent-based systems [74]. One of the main difference between MAS and HMAS is related to their main component: while the main component of MAS is the agent, the main component of HMAS is the holon. The others differences between MAS and HMAS are summarized in Table 4.2.

	<i>Multiagent system</i>	<i>Holonic multiagent system</i>
Thinking view	constructivism	holism (hierarchic and recursive)
Main component	agent	holon
Social capacity	Yes	Yes
Representation	Fine	Fine and coarse
Emergent properties	Yes	Yes
Conception	Heterogeneity of agents	Homogeneity of holons
Scaling	No	Yes

Table 4.2: Main differences between MAS and HMAS

As shown on Table 4.2, in modeling and simulation of complex system, MAS can exhibit a behavior close to the real behavior of the system source but may have difficulty to scale [50, 66]. In contrary to MAS, HMAS can scale better and can exhibit both fine and coarse behavior [51]. More generally, HMAS is the subject of more and more research [53, 50, 31] and have several advantages for designing a complex system, as listed below:

- **Reduction of complexity:** HMAS paradigm allows to divide a complex system in views or perspectives in order to reduce the number of entities involved and decrease the complexity of the process [122].
- **Emergent properties:** HMAS is able to represent emergent properties [51, 36]. In fact, emergent properties raise up toward the top of the holarchy i.e. behaviors of holons become more and more strategic toward the top of the holarchy. In contrary, toward the bottom of the holarchy, behaviors of holons become more and more operational.
- **Several levels of detail:** HMAS allows to represent a complex system under several points of view ranging from micro to macro through meso. Moreover HMAS can allow to build more than three levels of detail.
- **Linking of the levels of detail:** A holarchy is an effective solution to link micro, meso and macro level [46] through vertical communication. Link levels of detail can help to understand the influence of macro level on the micro level.
- **Dynamic adaptation of the levels of detail:** HMAS allows to migrate dynamically from one representation to another according to several criteria like visualization, computational resources etc. [143, 1]. HMAS is one of the suitable solution managing the compromise between simulation accuracy and available resources [51].
- **Scaling:** . As stated before, MAS has difficulty to scale [109, 50] while HMAS can scale [51, 31, 36]. HMAS becomes therefore an appropriate paradigm to deal with large scale distributed phenomena [51, 122].
- **Stability:** HMAS covers aspects of both hierarchical and heterarchical control approaches [124]. 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 [14].

In summary, HMAS is a suitable paradigm allowing the modeling and simulating of large-scale complex system [119, 51]. Moreover, HMAS have been widely used for large-scale modeling and simulation [46, 45, 50, 51, 145]. One useful question is therefore how to design a system with HMAS? Elements of answers to this question are described in the following section.

4.5/ MODELING A LARGE-SCALE COMPLEX SYSTEM USING HMAS

The process of building a HMAS is mostly different with the process of building more traditional software systems because it introduces new design and development issues [26]. In fact, several phases are important for building a complex system using HMAS paradigm: the definition of the holonic organization, the definition of the direction for holonification, the definition of the grouping or splitting criterion and the definition of multilevel indicators.

4.5.1/ HOLONIC ORGANIZATION

There are some general possibilities to structure a community of holons. Fischer et al. [44] identifies three main possibilities presented in Figure 4.5, those are:

- **Federation:** full sub-holons autonomy. Super-holon is a set of full autonomous sub-holons as shown on Figure 4.5a. Super-holon in federation is realized exclusively through cooperation among the sub-holons.
- **Fusion:** no sub-holons autonomy. Some sub-holons merge into a super-holon as shown on Figure 4.5b. A super-holon is the union of the sub-holons with capabilities that subsume the functionalities of the sub-holons. The merging holons give up completely their autonomy but they may be re-invoked when the super-holon is terminated. Realization of fusion holonic organization assumes procedures for splitting and merging holons that lead to the creation of a new holon.
- **Moderated group:** intermediate sub-holons autonomy. This holonic organization shown on Figure 4.5c considers a hybrid way of forming a super-holon, where sub-holons give up only part of their autonomy to the super-holon. Moderated group bring out the head holon which represents the super-holon outside to the rest of population. The competence of the head holon may range from purely administrative tasks to the authority to give directives to others sub-holons. Moreover, the head holon can have the authority to plan and negotiate for the super-holon, and even to incorporate new sub-holons or to remove some sub-holons.

In the next chapter, we will explain why this thesis focuses on fusion in order to build the holonic organization.

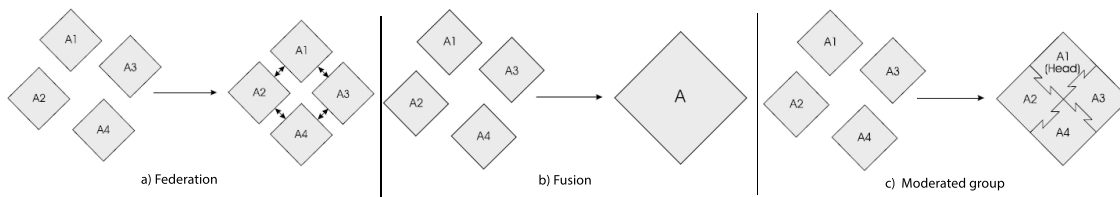


Figure 4.5: Holonic observation [44]

4.5.2/ DIRECTION FOR HOLONIFICATION

Holonification can be made from bottom to top, from top to bottom or by a fixed configuration. Moreover to manage holarchy over time, these directions can be combined. The principle of each holonification direction is presented in the following:

- **Downward holonification approach:** It identifies levels and holons by progressively partitioning the whole system downscale. In this approach holonification consists first of the modeling of the holon population (the highest super-holon of the system – the holon located at level $n + 2$ in Figure 4.6); then the holon population from the top to bottom is recursively partitioned/decomposed/divided/split into several sub-holons according to a point of view. This holonification approach is used in the university example presented in Section 4.4.1. Figure 4.6 presents this holonification approach.
- **Upward holonification approach:** it starts first with the modeling of atomic holons. Then the interactions between these atomic holons generates a complex behavior leading to the creation of some super-holons. In fact, some holons at each level interact together in order to bring out their super-holon at the immediate higher abstraction level of the system as shown by Figure 4.7. In other words, some holons aggregate/join/regroup/unite together to form their super-holon at the immediate higher abstraction level.
- **Prefixed configuration of holons:** it means that the holonification is made by the experts i.e. by the designers of the system. In this approach, all the holons of the system are identified in advance by the designers of the system. Moreover, the whole/part observation relationship (or containing/contained observation) of these holons are also identified by the designers of the system.

In the next chapter, we will explain why this thesis focuses both on upward and downward holonification.

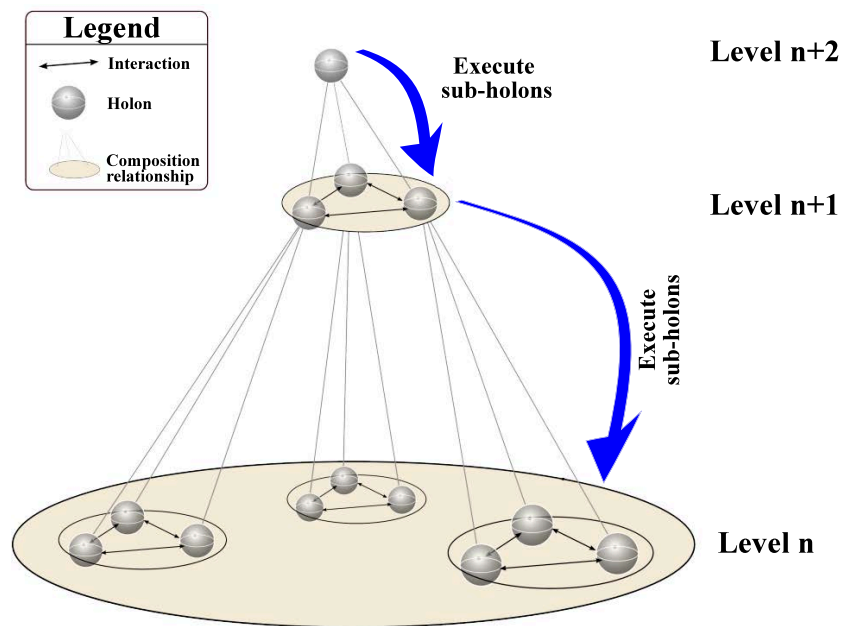


Figure 4.6: Downward holonification process

4.5.3/ GROUPING AND SPLITTING CRITERIA

To holonify a system, a grouping or splitting criterion is needed, or both. In fact, when the direction for holonification is made from bottom to top, a grouping criterion is needed and when the direction for holonification is made from top to bottom a splitting criterion is needed. Moreover, in the case of combining bottom-up and top-down directions for the holarchy management, both grouping and splitting criteria are needed. Grouping and/or splitting criterion allows to structure the composition of all holons of the system. There are several grouping/splitting criteria that are proposed in literature.

Gaud et al. [51] proposed affinity to structure the community of holons. The affinity measures the compatibility of two holons to work together to fulfill a shared objective. Affinity concept is exploited to dynamically aggregate holons and to obtain a scheduling holarchy that is coherent with the application objectives.

Esmaeili et al. [37] proposed centrality defined in social network research community to construct a multilevel holonic structure for a multiagent network. There are several kinds of centrality defined in social network. The authors adopt the concept of eigenvector centrality to define initial holons. Having built the initial holons, the other agents of the network try to join these holons to form the holarchy.

In order to enable a dynamic structure in HMAS, Rodriguez et al. [122] defined satisfaction criterion. Satisfaction measures the progress of the holon toward the accomplishment of its current goal.

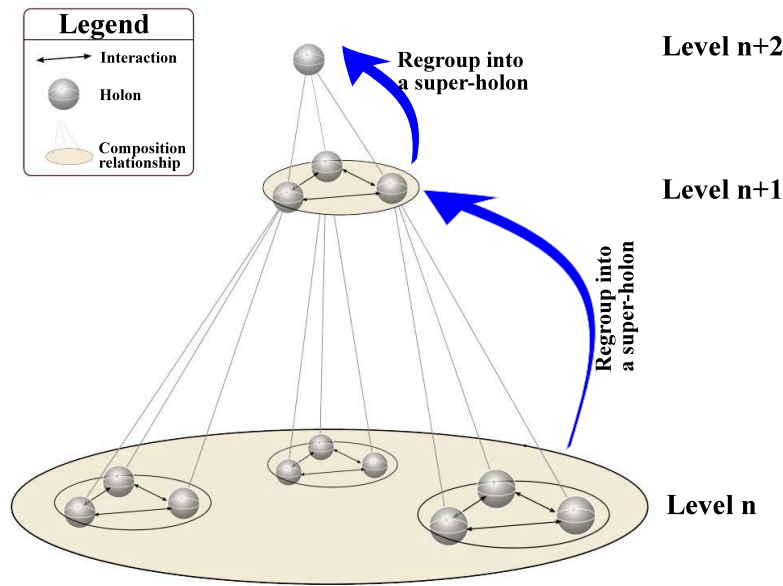


Figure 4.7: Bottom-up holonification process

There are several others grouping and/or splitting criterion available in literature [46, 60, 2]. The formulation of these grouping and/or splitting criterion is generally dependent on the application studied. Everyone must determine the suitable grouping and/or splitting criterion depending on the system to be studied.

4.5.4/ MULTILEVEL INDICATORS

In a HMAS, the level providing the most accurate simulation results is usually the microscopic level (level 0 in Figure 4.2). Demange [31] defines the accuracy of simulation of level l (with $l > 0$) as the difference between the results of the simulation of this level l and the microscopic level 0. In other words, when considering levels of detail higher than the microscopic level, the accuracy of the simulation decreases. The mesoscopic and macroscopic levels are only approximations of the behavior of the system that is well represented by the microscopic level from a certain point of view. Multilevel indicators in HMAS are tools to estimate the quality of the approximation of the higher levels compared to the microscopic level.

Several multilevel indicators have been proposed in literature. Contet et al. [25] proposed an indicator based on the computation of an energy as a state function both at the agent and system levels.

Other interesting methods based on statistical physics or thermodynamics have been proposed [89, 7]. These methods are based on the partition function Z from which all state functions in thermodynamic systems such as Gibbs function, free energy, enthalpy,

free enthalpy, derive.

There are several others multilevel indicators available in literature [45, 46, 51]. As the grouping and/or splitting criterion, the formulation of multilevel indicators is generally dependent on the application studied and therefore on the model of the system. Everyone must determine the best analogy to the problem being studied.

4.6/ CONCLUSION

This chapter presents the fundamentals of HMAS. Definitions, application case and core concepts of HMAS were presented. In addition, this chapter presents the stages needed for modeling a large-scale complex system using HMAS paradigm such as the holonic organization, the holonification direction, the grouping/splitting criteria and the multilevel indicator. Figure 4.8 presents a summary of HMAS. HMAS are systems composed of holons. Holons are particular agents that could be composed of other holons, interacting with each other for solving complex tasks. Figure 4.9 presents a summary of the holon concept.

Let's remind that the goal of this thesis is to build a dynamic multilevel model of large-scale complex systems i.e. systems exhibiting hierarchic behavior. As presented in this chapter, the hierarchical property and the intrinsic dynamic of holarchy favors the modeling and simulation of large-scale complex systems. Therefore HMAS seems a suitable solution to address the general problem of this thesis. To this end, the work framework of the design of such HMAS have to be defined. This will done in the next chapter of this thesis.

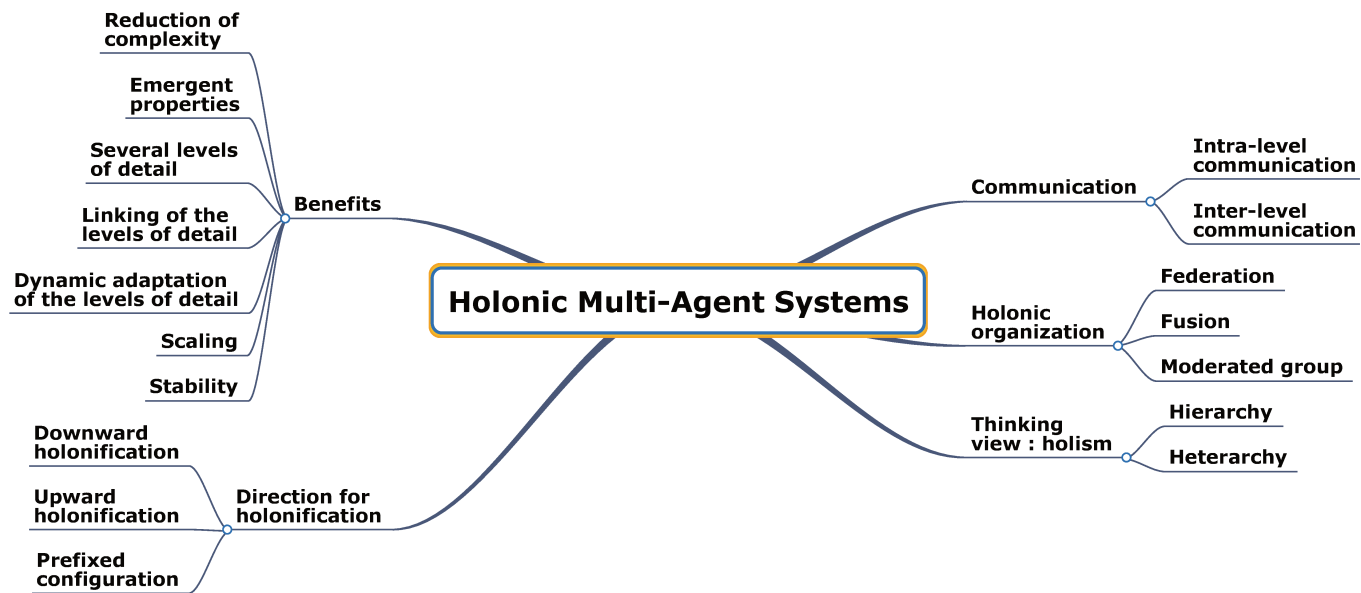


Figure 4.8: Summary of HMAS

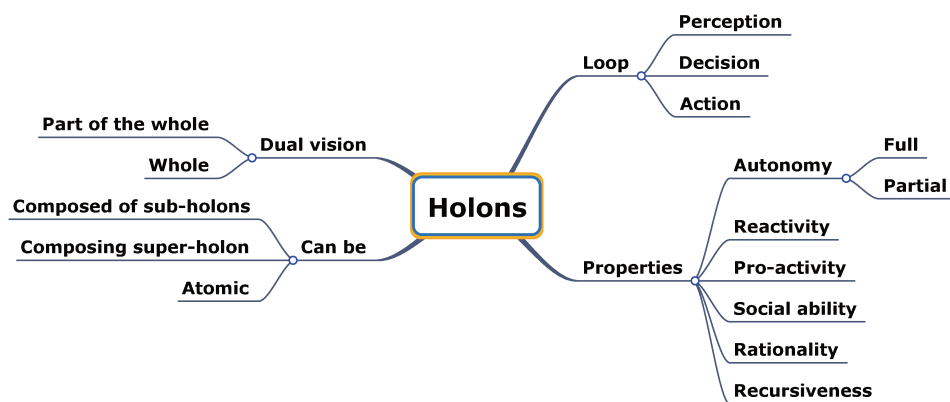


Figure 4.9: Summary of Holons

II

THE DYNAMIC AND HOLONIC MULTILEVEL MODEL OF LARGE-SCALE COMPLEX SYSTEM: APPLICATION TO ROAD TRAFFIC

RESEARCH METHODOLOGY AND CONTRIBUTIONS

5.1/ INTRODUCTION

The goal of this chapter is twofold: (i) to give more details on the general problem of this thesis by summarizing the bibliographical work done in the previous chapters, and (ii) to set out the hypothesis, constraints and research questions (RQ) on which the contribution is based.

From what we have seen in Chapter 2, road traffic can be considered as a large-scale complex. In fact, road traffic is composed by a large number of heterogeneous entities (car, trucks, bike etc.) having a non-linear graph of interactions. Moreover, road traffic is a geographically distributed phenomenon and exhibits a behavior at microscopic, mesoscopic and macroscopic level. Some monolevel models of traffic i.e. models focusing either on microscopic, either on mesoscopic or either on macroscopic representation are outlined in Chapter 3. Each of them has its own benefits and drawbacks. For example, microscopic models are closest to the real behavior of the vehicles but may have difficulties to scale [50] and their calibration is difficult due to the number of parameters involved [64]; while macroscopic models have an acceptable computational cost and their calibration is easy [64] but they exhibit a coarsest behavior. Microscopic models are generally applied in urban area and cross section where accuracy is fundamental while macroscopic models are generally applied in highway in order to provide among other the relationship between traffic flow and density in order to explain congestion. Therefore, these points of views taken individually (monolevel models of traffic) do not allow to represent traffic from several perspectives. To solve this problem of monolevel models of traffic, multi-level models of traffic were proposed as presented in literature. However, as presented in Chapter 3, most of multilevel models of road traffic are static, i.e. connections between levels of detail are predefined and cannot evolve during run-time [10]. There are few dynamic multilevel models available in literature [10]. Moreover, the available dynamic

multilevel models of traffic generally focus only on two levels of detail, i.e. microscopic and macroscopic levels [129, 10]. However, microscopic level and macroscopic level are too far away, and a direct transition from microscopic to macroscopic for example leads sometimes to inconsistency [106, 18]. Mesoscopic level is thus usually used as an intermediary level to increase the consistency between a transition from microscopic level to macroscopic level or a transition from macroscopic level to microscopic level. Therefore it can be interesting to have a multilevel model of traffic taking more than two level of detail, i.e. taking into account microscopic, mesoscopic and macroscopic representation in order to increase the consistency.

Having briefly summarized the previous chapters, now let us recall the general problem of this thesis: **How to build a dynamic multilevel model of large-scale complex system with spatial environment such as traffic system supporting a combination of microscopic, mesoscopic and macroscopic representations?** Let's remind that the application case of the proposal of this thesis is road traffic. Therefore, the model to be proposed must satisfy the main constraints of any multilevel model of road traffic those are [11]:

CONSTRAINT 1: COMPATIBILITY

The levels of detail integrated must be compatibles i.e. a methodology to switch from one level of detail to another is needed.

CONSTRAINT 2: CONSERVATION

No individual should be lost during the transition between two heterogeneous levels of detail. In other words, there is a conservation of the number of individuals among all the different levels.

5.2/ HYPOTHESIS AND RESEARCH QUESTIONS

Relying on the general problem presented above, we need to identify which methodology or paradigm is suitable to deal with our goal that is to build a dynamic multilevel model of large scale complex system with spatial environment. To this end, one paradigm caught our attention that is Holonic Multi-Agent System (HMAS); because, as presented in Chapter 4, HMAS is a suitable paradigm allowing to dynamically model a large-scale complex system exhibiting several levels of detail [53, 44]. Moreover, HMAS allows to model microscopic, mesoscopic and macroscopic representations of a system and

allows also to model transitions between these representations according to a policy or protocol defined by the designer. The previous enables us to make the following hypothesis.

HYPOTHESIS

HMAS is a suitable paradigm for the dynamic multilevel modeling and simulation of large-scale complex system with spatial environment such as large-scale traffic.

HMAS is a hierarchical structure of recursive holons (agents composed by agents). As stated before in Chapter 4, HMAS allows two types of interactions between holons: intra-level interactions, i.e., interactions between holons at the same level of detail and inter-level interactions, i.e., interactions between holons at different levels of detail.

Having made the hypothesis that HMAS is suitable to build our dynamic multilevel model of large-scale complex system with spatial environment such as large-scale traffic, then the intra and inter relationship between the holons of our HMAS need to be defined. This leads this thesis to define four research questions to tackle.

5.2.1/ RQ1: HOLONIC ORGANIZATION

Holonic organization refers to intra-holonic relationship, i.e. it concerns the degree of sub-holonic autonomy and covers the spectrum from full sub-holonic autonomy to a total lack of autonomy. RQ1 related to the holonic organization is formulated as follows:

RESEARCH QUESTION 1

What is the suitable holonic organization enabling to model large-scale complex system with spatial environment such as large-scale traffic?

Chapter 4 has presented the three main holonic organization available in literature: federation (full sub-holons autonomy), fusion (complete lack of sub-holons autonomy) and moderated group (medium sub-holons autonomy). To tackle RQ1, we can therefore focus either on federation, either on fusion or either on moderated group. This thesis focuses on fusion (more details are provided in the next chapter).

5.2.2/ RQ2: HOLONIFICATION METHODOLOGY

Knowing the degree of autonomy of the sub-holons, the other interesting question is to determine the methodology used for the formation of super-holons or to re-invoke sub-holons. In fact, fusion allows several sub-holons to merge forsaken completely their autonomy in order to create a new super-holon and to re-invoke them when needed. Creating some super-holons implies creation of new upper level of detail while re-invocation of sub-holons implies retrieving the previous level of detail. Realisation of fusion requires a methodology for splitting and/or merging holons. RQ2 is formulated as follows:

RESEARCH QUESTION 2

What is the methodology allowing to create upper levels or to re-invoke lower levels of the holarchy?

Designing a HMAS of large-scale complex systems, such as traffic systems refers to the modeling and simulation of the corresponding holarchy of the system studied. Holarchy is composed by several levels of detail and three main holonification directions are proposed in literature to build it: upward, downward and prefixed. Each holonification direction has its own benefits and drawbacks. For example, upward holonification leads to raise up emergent properties without a formal specification of a global behavior but can not guarantee in advance a particular desired global behavior of the system; while downward holonification reduces the complexity of system downscale but suffers from the sensitivity to changes in user requirements and global conceptual design. In order to combine the benefits of both upward and downward approaches, we use them for the management of holarchy. Therefore this thesis proposes a methodology to migrate from one level of detail to another on the two previous directions: from lower to upper level and from upper to lower level.

5.2.3/ RQ3 : GROUPING/SPLITTING CRITERION

Knowing the holonification methodology, another interesting question is to determine the criteria needed to build the new holons. RQ3 is formulated as follows:

RESEARCH QUESTION 3

What is the suitable grouping and/or splitting criterion required for the formation of the new holons for modeling large-scale complex systems such as traffic systems?

As stated in chapter 4, grouping and/or splitting criterion is application dependent. In this thesis, both grouping and splitting criteria are proposed because we use both upward and downward holonification. In the first hand, the grouping criterion proposed is based on density. Density allows us to find the sub-holons sharing some common properties such as speed, interdistance etc in order to create the corresponding super-holons. In the second hand, the splitting criterion proposed is based on probabilistic distribution. Probabilistic laws allow us to find how to decompose one super-holon into a set of sub-holons i.e. to re-invoke sub-holons.

Furthermore the formation of the new holons proposed have to guarantee the constraint 2 (conservation constraint) presented above. This means that no sub-holons should be lost during the re-invocation of sub-holons.

5.2.4/ RQ4: MULTILEVEL INDICATOR

Each multilevel model has to guarantee compatibility between the different levels of detail involved. That means that a methodology allowing a transition from one level of detail to another is necessary. This is generally done by a set of simplification and assumptions because of the heterogeneity of the levels of detail those can have different parameters. Therefore investigating the consistency of the process of migrating from one level of detail to another become important.

RESEARCH QUESTION 4

How to evaluate the consistency during transition from one holarchical level to another?

Tackling RQ4 allows this thesis to define multilevel indicators enabling the thesis to measure the error produced by the holonification. This helps us to discuss about the Constraint 1 related to compatibility between heterogeneous levels of detail. In literature the multilevel indicators is generally application dependant. This thesis focuses on standard deviation which is a well known statistical concept allowing to measure dispersion of a set of data.

5.3/ CONTRIBUTIONS

The goal of this thesis is to model a dynamic multilevel model of traffic system allowing to take into account microscopic, mesoscopic and macroscopic representations using a HMAS. To this end, this thesis proposes some solutions allowing to address the research questions raised previously. Figure 5.1 presents the research methodology of this thesis.

The contributions of this thesis are organized as follows:

- In Chapter 6 a holonification model of large-scale complex system such as large-scale road traffic is presented. RQ1, RQ2 and RQ3 are discussed.
- In Chapter 7 a dynamic holarchy management is presented. RQ2 and RQ4 are discussed as well as Constraint 1 and Constraint 2.
- In Chapter 8 an application to highway is presented. RQ4 is discussed. Furthermore the hypothesis is validated based on experiments.



Figure 5.1: Summary of research Methodology

HOLONIFICATION OF A LARGE-SCALE TRAFFIC SYSTEM

6.1/ INTRODUCTION

The goal of this thesis is to build a dynamic multilevel model of large-scale complex system such as road traffic. In the previous chapter, this manuscript has made the hypothesis that HMAS is a suitable approach to this end. In fact, HMAS is an interesting approach allowing to divide the system studied in perspectives in order to reduce the number of entities involved, to decrease the complexity of the process and therefore to deal with large-scale complex systems [122]. Let us recall that a HMAS is a hierarchy of recursive holons. The principle of HMAS is: (i) a number of holons can be created and coalesced to form other higher-level holons, generating thus a hierarchical system from lower to upper level, and/or (ii) a number of holons can be created and split to form other lower-level holons, generating also a hierarchical system from upper to lower level. Therefore to build a multilevel model of large-scale complex system such as traffic system by a HMAS, a methodology to manage the structure of the HMAS named holarchy is needed.

The goal of this chapter is twofold: (i) it describes the process of creating higher levels holons (super-holons) based on a set of lower levels holons (sub-holons), and (ii) it presents the idea of retrieving (re-invocation) of sub-holons from their super-holon. Therefore, the main contributions of this chapter are: (i) a methodology to create a super-holon from a set of sub-holons (upward approach), (ii) a criterion enabling to group similar holons into a super-holon (upward approach), and (iii) the principle of the methodology enabling to split a super-holon into a set of sub-holons i.e. retrieve sub-holons from the super-holon (downward approach).

This chapter is structured as follows. Section 6.2 presents the holonic organization defining the autonomy of holons. Section 6.3 presents the upward methodology to create upper levels and the corresponding criterion used to regroup some holons into a super-

holon. Section 6.4 presents the downward holonification and the criterion used to decompose a super-holon into a set of sub-holons.

6.2/ FUSION AS THE HOLONIC ORGANIZATION OF TRAFFIC

As asserted in the previous chapters, there are three main holonic organizations available in literature: federation, fusion and moderated group [44]. Each of them is application dependent, i.e. each of them is selected according to the source system to model. This thesis focuses on fusion for the holonic organization of road traffic system. In fact, fusion in HMAS was already successfully used to model several aspects of traffic such as pedestrian traffic [51] to model the displacement of pedestrians, urban traffic [2] for intelligent traffic control, etc. Moreover, pedestrian traffic for example has some common properties with road traffic such as sharing together the road infrastructure, exhibiting several levels of detail (individuals, groups of individuals, flow), etc.

Fusion allows to merge a set of sub-holons into a super-holon and to retrieve the sub-holons when the super-holon is terminated, by the need of simulation or by the will of the designer. This ability makes fusion well suited for optimization needs, i.e. well suited to save computational cost. In fact, in contrary to federation and moderated group where all the holons (super-holons and sub-holons) of the system can be simultaneously simulated, in fusion, only the super-holons are generally simulated because the sub-holons have completely forsaken their autonomy, i.e. the sub-holons are idle. Therefore as stated before, fusion allows to save computational cost in the management of the holarchy and thus well suited for modeling and simulation of large-scale complex systems [51, 2] which is the goal of this thesis.

The realization of fusion assumes a methodology for merging a set of sub-holons (resp. splitting a super-holon) in order to create a super-holon (resp. to retrieve sub-holons). This is done in the next sections as follows: Section 6.3 is dedicated for the methodology to create super holon while Section 6.4 is dedicated for the methodology to retrieve sub-holons.

6.3/ UPWARD DENSITY-BASED HOLONIFICATION

This section describes the general principle of our upward methodology, which is based on the grouping of similar entities. To this end, this section is structured as follows: first, this thesis presents why to group the entities of the traffic system. Then the methodology and the criterion used to group these entities are presented. And finally, algorithms enabling to realize this task are outlined.

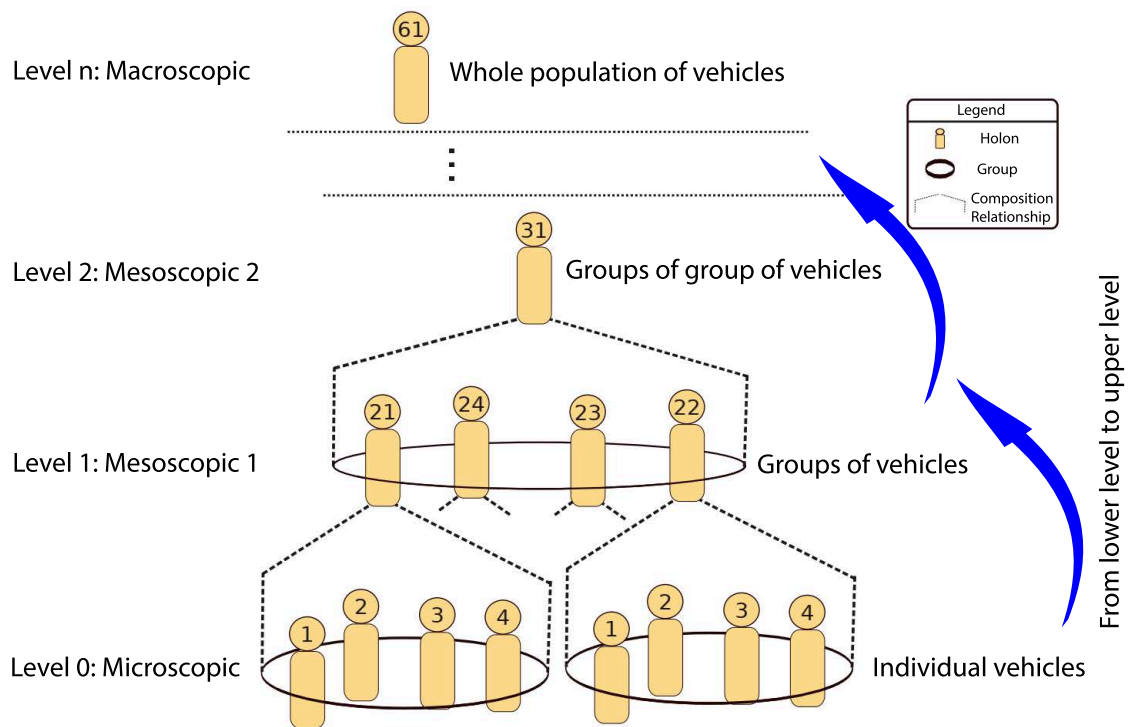


Figure 6.1: Example of upward vehicles simulation holarchy

6.3.1/ THE BENEFITS OF THE GROUPING OF SIMILAR ENTITIES OF TRAFFIC

In the modeling and simulation of large-scale complex system such as traffic system, in order to highlight the need of the grouping entities of traffic, let us assume the following example. Let's assume that there are some vehicles to simulate (vehicles at level 0 of the holarchy in Figure 6.1) under computational resource constraints. In order to allow such kind of simulation, the involvement of upper levels is necessary. To this end, a methodology enabling to group similar vehicles in order to create level 1 of the holarchy and then simulate the system at level 1 and so on has to be defined. HMAS is a suitable paradigm to define a such methodology allowing the scalability of the system [31, 1]. Moreover, by the grouping of the entities of a system, the HMAS can:

- **Represent the system from several perspectives:** A HMAS by its ability to represent a system from several perspectives, allows to link the different levels of detail and therefore can contribute to understand the influence of macro level to micro level
- **Obtain data at different representations:** A HMAS can allow to get data of the system source at several levels of detail

- **Enable a dynamic adaptation of the simulated representation:** A HMAS can allow to save the computational cost by a dynamic adaptation of the levels of detail during simulation i.e., a transition from one representation to another for lack of computational resources, needs of the simulation or by the will of the designer.

As outlined in the previous chapters, several methodologies have been proposed to group entities in order to build and manage the holarchy, such as the works of Esmaili et al. [37] who proposed a method to construct a multi-level holonic structure for a multi-agent network based on the centrality of the agents, or the works of Gaud [50] who proposed a method to build the holonic multilevel models of pedestrians through physic laws. These methodologies are generally application-dependent and in our case, we need therefore a such methodology fitting with road traffic system.

6.3.2/ THE FRAMEWORK OF BUILDING THE UPPER LEVELS OF HOLARCHY

This section presents the framework or the general principle of the methodology proposed to build the upper levels of holarchy. The model following this framework enabling to group the entities of traffic system is described in Section 6.3.4.

The idea of our methodology is to group similar vehicles at the immediate higher level within the holarchy. Figure 6.1 presents an example of traffic scenario built by the upward holonification process. In fact from bottom to top, vehicles are clustered in groups of vehicles, groups of groups of vehicles, and so on.

The principle proposed to cluster similar vehicles is inspired by clustering in evolving data streams [85]. In clustering in evolving data streams, since massive data flows objects arrive continuously with high speed by sensors, it becomes impossible to store all the data in memory, even in hard disk [85]. Moreover, the limited processing time, i.e. the computational cost of the execution is an important challenge in clustering in evolving data streams. A common way to deal with these challenges is to maintain the summaries over the data instead of the original raw data and use these summaries for clustering [20, 81]. This can be done to save the computational cost. This thesis intends to adapt this idea to traffic simulation. In this case for example, the raw data could be assimilated to the individual vehicles and the summaries of the raw data could be assimilated to the groups of individual vehicles. Therefore, following the principle of clustering in evolving data stream, under computational resource constraints, by the will of the designer, or to obtain data at different representations etc. instead to simulate individual vehicles, we can simulate the corresponding group of vehicles. And this process can be repeated as presented in Figure 6.1 going up to the holarchy.

Clustering vehicles in order to bring out some groups of vehicles is made according to a point of view. In fact, vehicles are heterogeneous by nature (trucks, car, bus etc.) and

characteristics allowing to group them need to be identified as well as a definition of what is a group of vehicles.

Definition 29: Group of vehicles, inspired by Gaud [50]

A group of heterogeneous vehicles consists of a set of vehicles sharing some common or similar characteristics. It models a set of vehicles interacting together.

In traffic system, several examples of groups of vehicles can be observed such as platoons, convoys, etc. The proposal is based on the notion of group of vehicles and could be adapted either for platoon, convoy or other groups of vehicles. In the following, this thesis focuses on convoy in order to define the common characteristics share by the vehicles belonging to a group of vehicles.

According to Vèque et al. [152], on both highways and urban areas, vehicles follow one another on a line and tend to regroup in convoys. The vehicles belonging to a convoy have a quasi-identical speed. Speeds of vehicles belonging to a convoy are therefore sensibly similar. Moreover, beyond the speed similarity among vehicles belonging to a convoy, there are others characteristics which are similar between them. A convoy is defined by the following.

Definition 30: Convoy, inspired by Vèque et al. [152]

A group of vehicles is within a convoy if:

1. they have approximately the same speed,
2. they move on the same lane,
3. the gap between them (interdistance) is approximately equal.

Convoys are therefore groups of vehicles sharing several common characteristics. Convoys are regularly observed in real traffic scenarios. Figure 6.2 depicts a traffic scenario having some convoys. Among vehicles belonging to a convoy, there is one vehicle which particularly affects all the convoy named the head, e.g. vehicle v_{20} on Figure 6.2. In fact, the head of convoy imposes its speed to all the convoy, particularly if change lane is not possible. The others vehicles within the convoy are the followers, e.g. v_{16} , v_{17} , v_{18} and v_{19} in lane 3 on Figure 6.2.

Furthermore, it is not all vehicles that belong to convoys. There are also single vehicles, i.e. vehicles moving at their desired speed, e.g. v_1 , v_9 , v_{14} , v_{15} on Figure 6.2. Single vehicles are free vehicles. Therefore, the traffic scenario depicted by Figure 6.2 can be decomposed by convoys and single vehicles. More generally, let's assume that any traffic scenario can be decomposed by:

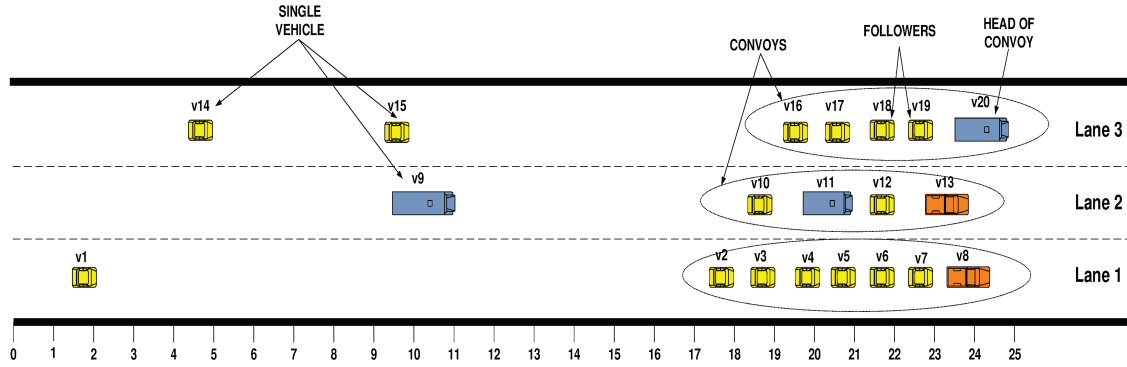


Figure 6.2: Traffic short case

(i) **a set of convoys,**

(ii) **a set of single vehicles.**

In summary, Figure 6.3 is as an example of the principle of the grouping process. As shown on this figure, some vehicles will regroup into one vehicle, which has a summary of the features of regrouped vehicles at the immediate higher level of detail. More precisely, the fine representation depicts 9 vehicles and the coarse representation depicts 3 vehicles such that the group formed by 7 vehicles is represented by one vehicle which is the summary of the 7 previous vehicles.

To allow such grouping process, a similarity criterion enabling to measure the similarity between vehicles is needed. Several similarity criteria have been proposed in literature. Gaud [50] proposed to use the affinity concept to measure similarity between pedestrians. Esmaeili et al. [37] proposed centrality to construct a multilevel holonic structure for a multiagent network, Rodriguez et al. [122] proposed satisfaction to measure the progress of the entities toward the accomplishment of their goal. Similarity criterion is generally application dependant. This thesis proposes “density” as a similarity criterion used for the upward holonification of our traffic system.

6.3.3/ DENSITY BASED GROUPING CRITERION

The grouping criterion is based on density that is an adaption of DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm [39]. First let us present DBSCAN.

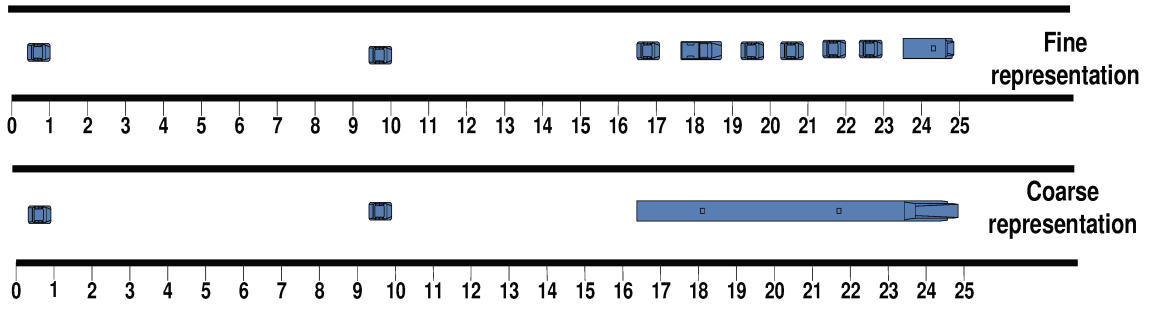


Figure 6.3: Fine/coarse representation that is lower/upper level representation

6.3.3.1/ BASIC NOTIONS OF DENSITY-BASED SPATIAL CLUSTERING OF APPLICATIONS WITH NOISE ALGORITHM

Ester et al. [39] proposed the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) for data clustering. DBSCAN is a density-based clustering algorithm. In fact, given a set of objects in some spaces, DBSCAN groups together objects that are closely packed together (objects with many nearby neighbors), marking as outliers objects that lie alone in low-density regions (whose nearest neighbors are too far away). DBSCAN is one of the most common clustering algorithms and widely cited¹ in scientific literature. In 2014, DBSCAN was awarded and therefore received the test of time award² at the leading conference on “Knowledge Discovery and Data mining” (KDD-14).

The problem that algorithm DBSCAN tries to solve can be defined as follows: given a database of n data objects $D = \{o_1, o_2, \dots, o_n\}$, DBSCAN partitions database D into k clusters $C = \{C_1, C_2, \dots, C_k\}$ based on a similarity measure. This process is called density based clustering. $C_i \subseteq D, i = \{1, \dots, k\}$ are called clusters. There is no nested cluster. In fact, $\forall i = \{1, \dots, k\}, \cap_{i=1}^k C_i = \emptyset$.

DBSCAN uses a radius value (a fixed threshold) to determine dense regions named Eps . DBSCAN uses also $MinPts$ parameter which is the minimum number of neighbors within Eps radius.

The basics concepts and terms explaining the DBSCAN algorithm can be defined as follows [39, 9].

Definition 31: Neighborhood

It is determined by a distance function (e.g. Euclidean, Manhattan distance) between two objects q and p , denoted $dist(q, p)$.

¹More than 15,335 citations according to Google Scholar, on September 10th, 2019

²<http://www.kdd.org/awards/view/2014-sikdd-test-of-time-award-winners>

Definition 32: Eps-neighborhood

The Eps-neighborhood of object q is defined by $\{p \in D : \text{dist}(q, p) \leq \text{Eps}\}$.

Definition 33: Core object

A core object refers to such object that its neighborhood of a given radius Eps has to contain at least a minimum number MinPts of other objects (Fig. 6.4c).

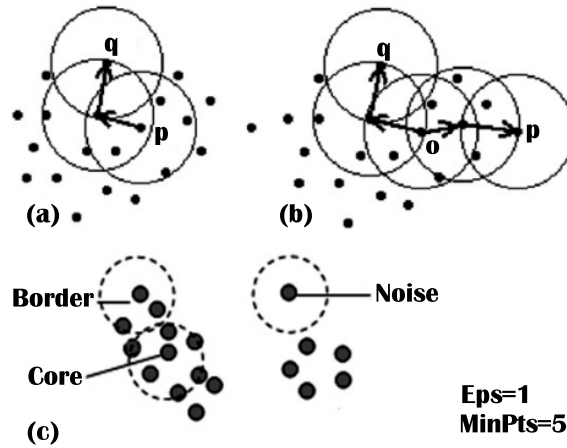


Figure 6.4: Terminology of DBSCAN: (a) q density-reachable from p ; (b) q and p density-connected to each other by o ; (c) border, core and noise object.

Definition 34: Directly density-reachable

An object q is directly density-reachable from the object p if q is within the Eps-neighborhood of p , and p is a core object.

Definition 35: Density-reachable

An object q is density-reachable from the object p with respect to Eps and MinPts if there is a chain of objects $q_1, \dots, q_n, q_1 = p$ and $q_n = q$, such that q_{i+1} is directly density-reachable from q_i with respect to Eps and MinPts , with $i = \{1, \dots, n\}, q_i \in D$ (Fig. 6.4a).

Definition 36: Density-connected

An object q is density-connected to object p with respect to Eps and MinPts if there is an object $o \in D$ such that both q and p are density-reachable from o with respect to Eps and MinPts (Fig. 6.4b).

Definition 37: Density-based cluster

A cluster C is a non-empty subset of D satisfying the “maximality” and “connectivity” requirements that is:

$\forall q, p$: if $p \in C$ and q is density-reachable from p with respect to Eps and $MinPts$ then $q \in C$

$\forall q, p \in C$: q is density-connected to p with respect to Eps and $MinPts$

Definition 38: Border object

An object q is a border object if it is not a core object but density-reachable from another core object (Fig. 6.4c).

DBSCAN algorithm starts with the first object q in database D , and finds all neighbors of q within Eps distance. If the total number of these neighbors is greater than $MinPts$ and q is a core object, a new cluster is created: the object q and its neighbors are assigned into this new cluster. Then, DBSCAN iteratively collects the neighbors within Eps distance from the core object. The process is repeated until all of the objects have been processed.

In order to determine whether a set of objects is similar enough to be considered a cluster or not, DBSCAN need a distance measure $dist(i, j)$ that tells how far objects i and j are. The most common distance measures used in literature is the Euclidean distance [9]. Euclidean distance is defined as follows:

$$dist(i, j) = \sqrt{(x_{i1} - x_{j1})^2 + (x_{i2} - x_{j2})^2 + \dots + (x_{in} - x_{jn})^2} \quad (6.1)$$

where $i = (x_{i1}, x_{i2}, \dots, x_{in})$ and $j = (x_{j1}, x_{j2}, \dots, x_{jn})$ are two data objects of dimension n .

6.3.3.2/ BENEFITS AND DRAWBACKS OF DBSCAN

DBSCAN algorithm has several advantages and drawbacks. On the first hand, the main advantages of DBSCAN are:

- DBSCAN does not require specifying the number of clusters in the data a priori. In fact, in contrast with several others clustering algorithms, DBSCAN does not require the predetermination of the number of clusters and has been proven its ability of processing very large databases [9].
- DBSCAN is capable of discovering clusters with any arbitrary shape such as linear, concave, oval, etc. and at the same time DBSCAN can distinguish noise objects.

On the other hand the main drawback of DBSCAN is its incapacity to support clusters of different sizes [9]. In fact, for instance, Figure 6.5 shows a database with 50 objects.

There are twenty four objects in cluster C_1 , twenty four objects in cluster C_2 , and two additional noise objects O_1 and O_2 . C_2 is a denser cluster than C_1 (cluster densities are different from each other). On the first hand, if value of Eps is less than the distance between O_2 and C_2 , some objects in cluster C_1 are considered as noise object. On the other hand, if the value of Eps is greater than the distance between O_2 and C_2 , the object O_2 is not considered as noise object.

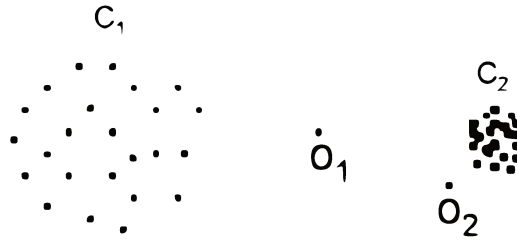


Figure 6.5: DBSCAN drawback: database example which contains clusters with different densities

6.3.3.3/ SUMMARY OF DENSITY BASED CRITERION

As stated before, this thesis focuses on the density criterion to build the structure of the HMAS of traffic ascending manner. This means that the very close interacting vehicles within the environment are similar. We use the idea of DBSCAN to group similar vehicles. In fact, DBSCAN groups together objects that are close to each other and marks as outliers the objects that are in low-density regions. In the same vein, following this idea of DBSCAN, our density based model will group together vehicles that are close to each other and marks as single the vehicles whose nearest neighbors are too far away. [Our extension of DBSCAN is called H-DBSCAN](#), i.e. Holonic DBSCAN (more detail in Section 6.3.4.2) in this thesis. One of the advantage of our model is that there is no outlier and therefore the main drawback of DBSCAN that is its incapacity to support clusters having different sizes is skipped. In fact, all the outliers according to DBSCAN are assigned as single vehicles in our model. This help us to build the upper levels according to the following methodology.

6.3.4/ BUILDING THE UPPER LEVELS OF HOLARCHY

In the previous sections, we have presented the general framework allowing to build the upper levels of the holarchy as well as the criterion proposed to group similar holons. In this section, the formal definitions of the structure of our HMAS and the algorithms proposed to build the upper levels of the holarchy are presented.

In this chapter, the focus is on the entities and their vertical interactions allowing them to

build the upper levels. The internal behaviors of each entity and horizontal interactions among them is described in detail in Chapter 7.

First, let us assume that we have a population of heterogeneous vehicles moving on a road. Our model depicts two types of holons:

- **Traffic Holons:** Traffic holons are individuals or a group of individuals within the traffic system. Traffic holons can be a vehicle-driver pair, or a group of vehicle-driver pairs, a group of group of vehicle-driver pairs etc. Traffic holon h_i^n is the i -th traffic holon at level n .
- **Cluster Unit Holon:** The cluster unit holons are particular holons created at each level of detail in order to simplify the holonification process. The cluster unit holons stand for a separate controllers whose goal is to group traffic holons at the current level of detail into traffic super-holons at the immediate higher level of detail within the holarchy. A cluster unit holon \mathcal{H}^n is the cluster unit holon at level n . There is always one cluster unit holon per level of detail.

In order to represent the interactions allowing to build the immediate upper level between the traffic holons and the cluster unit holon, Figure 6.6 outlines the organizational model that is applied at each level of detail of the holarchy. As shown on this figure, at each level of detail, the traffic holons send the messages to a cluster unit holon. The communication between the traffic holons and a cluster unit holon is horizontal and the messages sent represent the states variables (the features variables) of the corresponding traffic holons. The cluster unit holon gathers the features variables of all the traffic holons at the current level of detail and applies H-DBSCAN in order to group “similar” traffic holons.

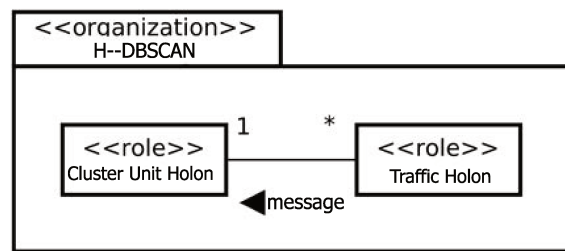


Figure 6.6: Organizational model of our proposal according to ASPECS [26] methodology's formalism

6.3.4.1/ FORMAL DEFINITIONS OF THE HMAS OF TRAFFIC

The HMAS can be defined as a triplet $\langle H, HI, VI \rangle$. H is the holarchy in term of composition. HI is the set of horizontal interaction among holons. VI is the set of vertical interaction among the different levels of the system.

A holarchy H , composed of $h \in \mathbb{N}^*$ levels, is defined as in Eq. 6.2, where $H^n, n \in \{0, \dots, h-1\}$ is the set of all holons at level n of the holarchy.

$$H = \{H^0, H^1, H^2, \dots, H^{h-1}\} \quad (6.2)$$

In the same way, Eq. 6.3 defines the set of all holons at level n of holarchy. h_i^n is the i^{th} traffic holon at level n . m_n is the number of traffic holons at the n^{th} level. \mathcal{H}^n is the cluster unit holon at level n . The total number of holons at level n is therefore $m_n + 1$.

$$H^n = \{h_1^n, h_2^n, \dots, h_{m_n}^n, \mathcal{H}^n\} \quad (6.3)$$

Let's assume that traffic holons can't be nested (disjoints traffic holons) that is:

$$\forall n \in \{1, \dots, h-1\}; i, j \in \{1, \dots, m_n\}; i \neq j \Rightarrow h_i^n \cap h_j^n = \emptyset \quad (6.4)$$

In addition to the holon set, there are interactions sets. HI is the horizontal interactions set among holons and be define by Eq. 6.5

$$HI = \{HI^0, HI^1, \dots, HI^{h-1}\} \quad (6.5)$$

The cluster unit holon at a given level interacts with all the traffic holons at the same level and Eq. 6.6 defines the horizontal interactions at each level of detail.

$$HI^n = \{(h_i^n, \mathcal{H}^n), h_i^n \in H^n, i = \{1, \dots, m_n\}\} \quad (6.6)$$

(h_i^n, \mathcal{H}^n) means: the traffic holon h_i^n interacts with the cluster unit holon \mathcal{H}^n . This interaction can be made through messages.

In addition to the horizontal interactions, there are vertical interactions. Vertical interactions is made by holons in two adjacent levels within the holarchy. VI is the set of interactions among levels, and is defined by Eq. 6.7

$$VI = \{VI^{(0,1)}, VI^{(1,2)}, \dots, VI^{(h-2,h-1)}\} \quad (6.7)$$

Inter-level communication is between traffic sub-holons and their traffic super-holon. In fact, since a traffic super-holon is a parent of their traffic sub-holons, traffic sub-holons communicate with their traffic super-holon.

$$VI^{(n,n+1)} = \{(h_i^n, h_k^{n+1}) : h_i^n \in h_k^{n+1}, \\ i = \{1, \dots, m_n\}, k = \{1, \dots, m_{n+1}\}, h_i^n \in H^n, h_k^{n+1} \in H^{n+1}\} \quad (6.8)$$

$h_i^n \in h_k^{n+1}$ means that traffic holon h_i^n is a traffic sub-holon of traffic holon h_k^{n+1} . m_n, m_{n+1} are the respective numbers of traffic holon at level n and level $n + 1$.

6.3.4.2/ ALGORITHMS TO BUILD UPPER LEVELS

As stated before, to build the upper level, all traffic holons at a given current level send all their states variables to the cluster unit holon and then, the cluster unit holons gathers all these states variables and applies the algorithm H-DBSCAN. The result of the algorithm H-DBSCAN highlights the similar traffic holons and help to build the upper level.

H-DBSCAN algorithm needs two parameters: *MinHol* and *Eps*. *MinHol* is the minimum number of traffic sub-holons that are required in order to create a traffic super-holon. *Eps* parameter is the distance metric as in DBSCAN. Moreover, in order to apply H-DBSCAN, a distance measure is needed between traffic holons at the same level, $dist(h_i^n, h_j^n)$. The distance measure tells how far traffic holon h_i^n and h_j^n are. In order to have a generic model, no specific distance in the model is formally chosen. Consequently, $dist(h_i^n, h_j^n)$ is the distance between two traffic holons h_i^n and h_j^n at the same level n .

Algorithm 1 presents the algorithm H-DBSCAN. Algorithm 1 needs the two additional algorithms 2 and 3.

Algorithm 1 Holonic DBSCAN: H-DBSCAN

```

1: function HDBSCAN(TH, Eps, MinHol)    ▷ TH represent traffic holons at a given level of detail
2:   SupHol ← 0;
3:   AllCompositeHol ← ∅
4:   for each not visited holon  $h \in TH$  do
5:     Mark  $h$  as visited
6:     Neighbours = RANGEQUERY(TH,  $h$ , Eps)
7:     if  $|Neighbours| < MinHol$  then
8:       Mark  $h$  as single
9:     else
10:      SupHol ← new super-holon                ▷ A composite super-holon
11:      EXTENDCLUSTER(TH,  $h$ , Neighbours, SupHol, Eps, MinHol)
12:      AllCompositeHol ← AllCompositeHol ∪ SupHol
13:    end if
14:  end for
15:  for each holon  $h \in TH \setminus AllcompositeHol$  do
16:    SupHol ← new super-holon                ▷ A single super-holon
17:    Add holon  $h$  to super-holon SupHol
18:  end for
19:  return SupHol
20: end function

```

In opposite to DBSCAN, Algorithm 1 does not have the outliers. All the outliers are assigned (lines 16 and 17) to a single traffic super-holon (not composite holon). The formed cluster is assigned to a composite traffic super-holon (lines 10 and 11).

Like DBSCAN, the H-DBSCAN algorithm has the advantage of flexibility. In fact, H-

Algorithm 2 Build the holon (a composite holon)

```

1: procedure EXTENDCLUSTER( $TH, h, Neighbours, SupHol, Eps, MinHol$ )
2:   Add holon  $h$  to super-holon  $SupHol$ 
3:   for each holon  $h' \in Neighbours$  do
4:     if  $h'$  has not been visited then
5:       Mark  $h'$  as visited
6:        $Neighbours' \leftarrow \text{RANGEQUERY}(TH, h', Eps)$ 
7:       if  $|Neighbours'| \geq MinHol$  then
8:          $Neighbours' \leftarrow Neighbours \cup Neighbours'$ 
9:       end if
10:    end if
11:    if  $h'$  do not belong to any super-holon then
12:      Add holon  $h'$  to super-holon  $SupHol$ 
13:    end if
14:  end for
15: end procedure

```

Algorithm 3 Build the Neighborhood of holon h

```

1: function RANGEQUERY( $TH, h, Eps$ )
2:    $N \leftarrow \emptyset$ 
3:   for each holon  $q \in TH$  do
4:     if  $dist(q, h) \leq Eps$  then
5:        $N \leftarrow N \cup \{q\}$ 
6:     end if
7:   end for
8:   return  $N$ 
9: end function

```

DBSCAN does not require specifying the number of clusters (super-holons) a priori. We can therefore have a variable number of holons at each level within the holarchy.

In the management of holarchy, after building upper level, it can be useful to go down in holarchy i.e. re-invocation of traffic sub-holons from their traffic super-holon. Therefore a downward holonification is also needed.

6.4/ DOWNWARD PROBABILISTIC DISTRIBUTION HOLONIFICATION

The principle of downward holonification is presented by Figure 6.7. As presented in this example, super-holons are split into several sub-holons, and thus a methodology to split one super-holon into several sub-holons is required.

To achieve the splitting, normal distribution is used. The normal distribution or, as it is also called, the Gauss distribution is the most undoubtedly important and popular distribution in statistics. Normal distributions are often used in the natural events to represent real-valued random variables whose distributions are not known [49]. Moreover, in agreement with previous studies [62, 61], it was found that a normal distribution is a good approximation for computing the values of the vehicles features' variables, such as veloc-

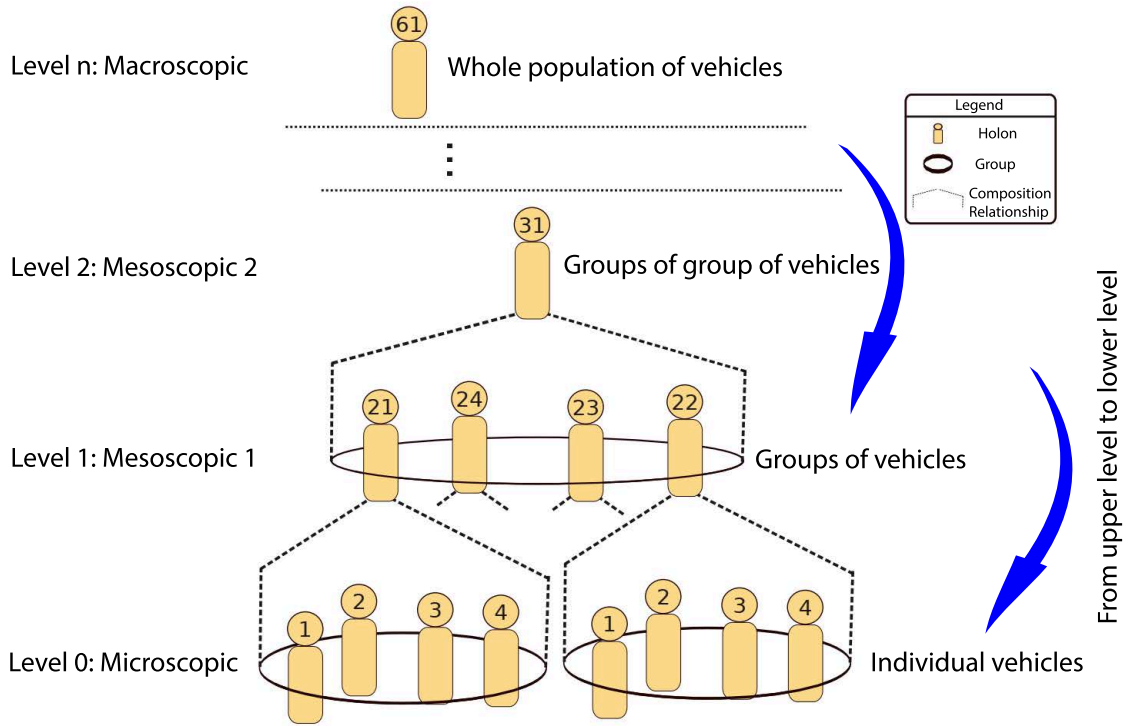


Figure 6.7: Example of downward vehicles simulation holarchy

ity distribution. Let's recall that the probability density of the normal distribution is given by Equation 6.9.

$$f(x; \mu, \sigma^2) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left\{ -\frac{1}{2} \left(\frac{x - \mu}{\sigma} \right)^2 \right\} \quad (6.9)$$

Where μ is a location parameter, equal to the mean, and σ the standard deviation.

For $\mu = 0$ and $\sigma = 1$, we refer to this distribution as the standard normal distribution. In many cases, it is sufficient to use this simpler form since μ and σ may be regarded as a shift and scale parameter, respectively.

Having presented normal distribution, the idea to re-invoke traffic sub-holons from their traffic super-holon is to assume that the states variables of traffic sub-holons grouped within a traffic super-holons follow a normal distribution of parameter μ and σ , which are parameters of the traffic super-holons. Parameters μ and σ are used to generate the parameters of the traffic sub-holons. Figure 6.8 presents the idea of the methodology used to re-invoke four traffic sub-holons from one traffic super-holon based on the parameters μ and σ of the traffic super-holon. More details on how to retrieve the features variables of the traffic sub-holons based on the features variables of a traffic super-holon as well as its parameters μ and σ are provided in Chapter 7.

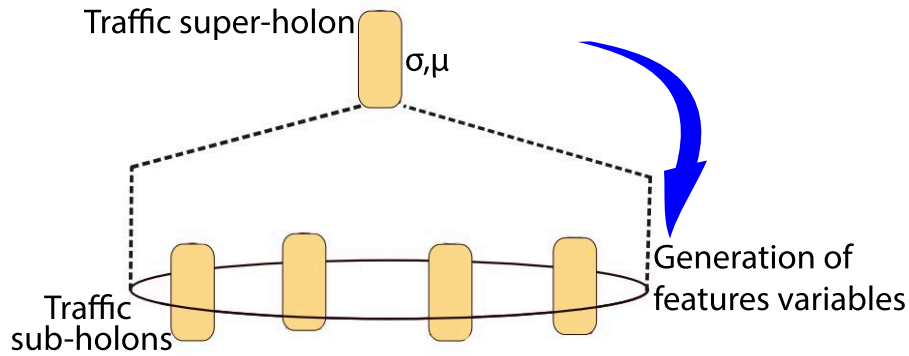


Figure 6.8: Downward gaussian generation of sub-holons

6.5/ CONCLUSION

The work presented in this chapter represents a first step towards the design of a dynamic multilevel model of traffic by a HMAS. Several research questions presented in Chapter 5 have been investigated in this chapter:

- **RQ1:** related to the holonic organization, fusion was selected to represent the way of the autonomy of holons are structured within the holarchy. Fusion fits well with several traffic problem such as pedestrians traffic, traffic control etc. In addition, related to the computational load, fusion is an interesting holonic organization.
- **RQ2:** related to the holonification methodology, an upward and downward methodology was presented to structure the holarchy. In fact, a methodology allowing to create upper levels of the holarchy is presented as well as the principle to go back in lower levels of the holarchy.
- **RQ3:** related to grouping and splitting criterion in order to find similarities between holons, a density based grouping criterion was proposed for the upward holonification. Moreover, this chapter proposes H-DBSCAN: an extension of the well know DBSCAN algorithm for multilevel purposes. For the downward holonification, probabilistic laws allow to decompose super-holons into a set of sub-holons.

Figure 6.9 presents a summary of this chapter. In addition to the methodologies presented in this chapter, it is necessary to define clearly the models of interactions between holons in order to execute dynamically the holarchy of traffic system. The dynamic interactions of holons is detailed in the next chapter.

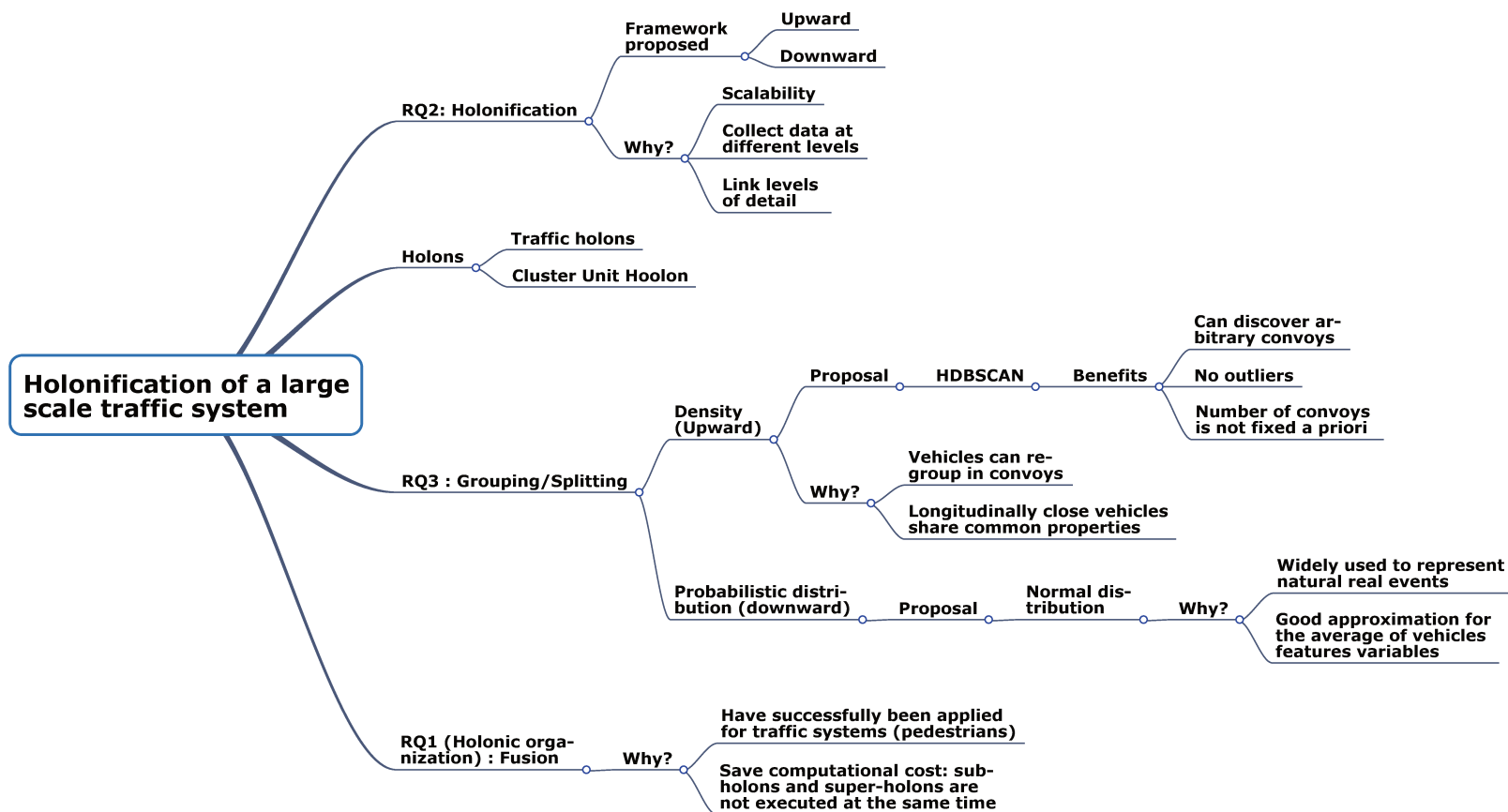


Figure 6.9: Summary of the holonification model of large-scale traffic

DYNAMICITY WITHIN THE HOLONIC MULTILEVEL MODEL OF TRAFFIC

7.1/ INTRODUCTION

Multilevel simulation principle aims to bring together, within the same simulation, simulated system entities at different levels of detail. Let us recall that a level of detail, or representation is a point of view on a system. Multilevel models allow therefore to represent a system from several perspectives. Multilevel model can be static or dynamic. In contrary to static multilevel model in which the levels of detail and their boundaries are predefined, in dynamic multilevel model, the same entities can dynamically change their representation by the needs of simulation, or the will of the designer. To allow this dynamic change of representation, it is necessary to manage the transitions between several levels of detail while guaranteeing the consistency of the simulation.

We recall that our goal is to build a dynamic multilevel model of large-scale complex system such as traffic system. To achieve this, we propose an approach based on the dynamic adaptation of the level of detail of simulation. The hypothesis that HMAS is appropriate to build a dynamic multilevel model of traffic is considered. Therefore, in Chapter 6, we have presented a methodology to create upper levels as well to go back in lower levels of the holarchy. In this chapter we focus on the dynamic holarchy management.

This chapter presents the following contributions: (i) a holonic model for dynamic management of the holarchy of traffic (ii) a definition of a multilevel indicator. The first contribution allows a dynamic adaptation of the level of detail of the simulated holarchy. In other words, we propose an approach for the dynamic transition between levels of detail of the holarchy representing traffic. The second contribution allows to measure the consistency of the transition process.

This chapter is structured as follows: Section 7.2 describes the general methodology enabling the dynamically management of the holarchy of traffic and Section 7.3 presents

an application of the previous methodology to the case of vehicles traffic entities with Intelligent Driver Model.

7.2/ FRAMEWORK FOR DYNAMIC MANAGEMENT OF HOLARCHY OF TRAFFIC

Firstly, let us recall that in the previous chapter, we have presented the two main holons of our system: the traffic holons and the cluster unit holon. In the first hand, traffic holons can be either a vehicle–driver pair either a group of vehicle–driver pairs. A traffic holon can therefore be seen either as a single entity, either as a composed entity (a set of several traffic sub-holons). Traffic holon h_{α}^i is the α -th traffic holon at level i . Cluster unit holons are holons that do not represent any real traffic system entity. Cluster unit holons are holons inserted to facilitate the multilevel modeling and simulation of the traffic system. Cluster unit holon \mathcal{H}^i is the cluster unit holon at level i .

The input of the multilevel simulation is a set of traffic holons and their related state variables. These input traffic holons form the level 0 of the holarchy of traffic and all these traffic holons are atomic. In order to allow the multilevel simulation of traffic, traffic holons have to be simulated at several levels of detail. Therefore, three mains questions are raised up those are:

1. **Why is a transition from one level of detail to another interesting?:** This question is widely discussed along the thesis. As stated before microscopic simulation tends to be the closest of the real behavior of entities simulated. However, microscopic simulation of large-scale complex systems remains a major challenge [51, 106]. In fact, as soon as we consider a microscopic simulation of several individuals and their relationships, the complexity of the system and associated computational costs increase. This leads therefore to bring out a dilemma common in the field of simulation: [management of a compromise between performance and accuracy](#). In other words, a compromise between simulation accuracy and availability of computational resources needs to be tackled for large-scale modeling and simulation of complex systems. In summary, transition from one level of detail to another can dynamically adapt the accuracy of the simulation according to the volume of available computational resources, i.e. allows the scaling of the system. Moreover, it can allow the representation of the system studied from several perspectives.
2. **When is a transition from one level of detail to another applied?:** To address this question, we propose a multilevel event based simulation, i.e. the multilevel simulation remains at the current representation until an event that causes the changing of the representation occurs. In fact, an event based approach is suitable

to deal with the scalability of multilevel simulation of large-scale system because there is no recalculation of the different states and variables of the system at each time step but only when an event occurs [104, 103, 31].

In our proposal, there are two events that can disrupts the multilevel simulation : “upward switch” and “downward switch”. On the first hand, an upward switch leads to changing the current representation to an upper level. For example, an upward switch can lead to make a transition from level 0 to level 1, from level 1 to level 2 and so on of the holarchy, as outlined in Figure 6.1 on page 87. The upward switch event is defined as follows:

Definition 39: Upward Switch

Upward switch event (or simply upward switch) is an event that triggers the transition from a current given level of detail to the immediate upper level of detail in the multilevel simulation.

On the second hand, a downward switch leads to change the current representation to a lower level. For example, a downward switch can lead to make a transition from level n to level $n - 1$, ..., from level 2 to level 1, from level 1 to level 0 of the holarchy as outlined in Figure 6.7 on page 99. We define a downward switch as follows:

Definition 40: Downward Switch

Downward switch event (or simply downward switch) is an event that triggers the transition from a current given level of detail to the immediate lower level of detail in the multilevel simulation.

Figure 7.1 presents an example of the level transitions of the of the example presented by Figure 6.1 on page 87 and Figure 6.7 on page 99.

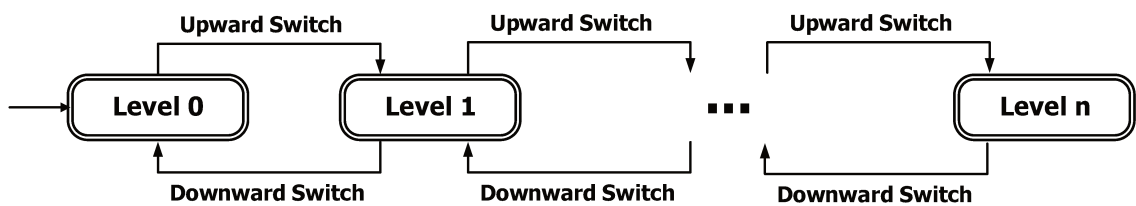


Figure 7.1: An Example of Level Transition of the Multilevel Simulation

In summary, three main cases are possible:

- a. When no switch event is received i.e. there is no disruption of the multilevel simulation. This scenario is called “no transition case”.

- b. When a disruption is caused by an upward switch leading the multilevel simulation to make a transition from the current representation to the immediate upper level. This scenario is called “transition to upper level case”.
- c. When a disruption is caused by a downward switch leading the multilevel simulation to make a transition from the current representation to the immediate lower level. This scenario is called “transition to lower level case”.

3. How is a transition from one level of detail to another applied?: Depending on the cases above, interactions between traffic holons and cluster unit holon are not the same. In each case, a specific scheme of interactions between holons and cluster unit holon is defined. In the following more details are provided.

7.2.1/ INTERACTION MODEL BETWEEN HOLONS WHEN NO TRANSITION

As stated before, no switch event implies that simulation remains at the current level, i.e. simulation keeps the same representation. If we assume that the current level is level i , without a switch event, the behaviors of holons are:

- **Traffic Holon:** Traffic holons are simulated at level i according to a time step model. In fact, in no transition case, at each time step, traffic holons perceive their environment and update their states according to a car-following model as shown by Figure 7.2. Time step model is usually used to simulate car-following models in literature [78, 147, 64].
Our proposal is hybrid, i.e. event-based regarding the transitions between different levels of detail and time step regarding the simulation of traffic holons at a given level of detail. In other words, event-based triggers simulation of inter-levels interaction while time step is used for intra-level simulation.
- **Cluster Unit Holon:** The cluster unit holon monitors the state of the system. To this end, the cluster unit holon takes a look on the hardware resources, such as CPU consumption, memory usage, etc. Additionally, the cluster unit holon takes care about the objectives of the simulation designer, such as the regions with interest for simulation. These elements can lead to create a switch event.

The algorithms of both traffic holon and cluster unit holon taking into account no transition case are presented in Section 7.2.4.

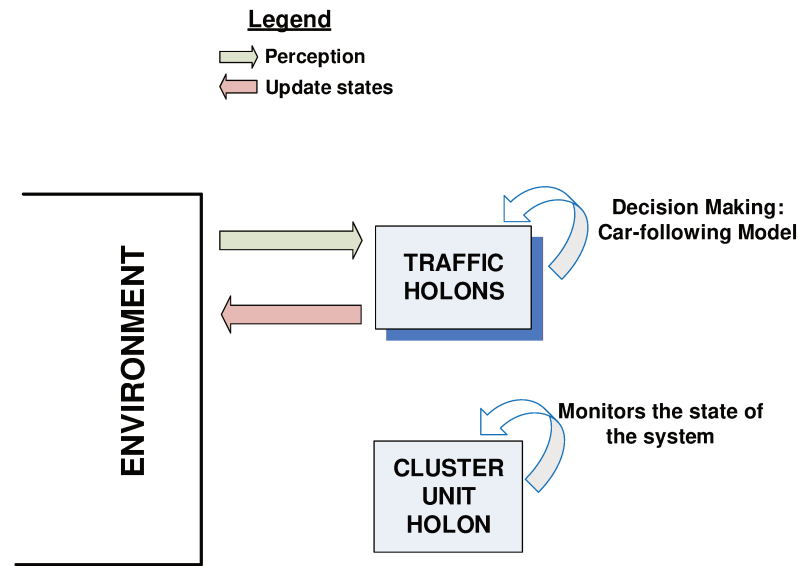


Figure 7.2: Interaction model in no transition case

7.2.2/ INTERACTION MODEL BETWEEN HOLONS WHEN TRANSITION TO UPPER LEVEL

To achieve a transition to upper level, we assume that all the upward transitions of holarchy are jumps of degree 1, i.e. for example it is not possible in our model to make a direct transition from level 0 to level 2 of the holarchy presented in Figure 6.1 on page 87. To perform such action, two transitions have to be performed: a first transition from level 0 to 1 and a second transition from level 1 to 2. The advantage is to allow a step transition in order to increase the consistency of the simulation [106]. If we assume that the current level is i , a transition to upper level represents therefore a migration from level i to level $i + 1$. This kind of transition involves a more coarser representation.

The interactions model between traffic holons and cluster unit holons are depicted by Figure 7.3. Firstly, the cluster unit holon at level i sends an upward switch event to traffic holons at level i as shown by arrow (1). All the traffic holons at level i send their states variables to cluster unit holon at level i shown by arrow (2). The cluster unit holon at level i gathers the states variables of all the traffic holons at level i and applies algorithm H-DBSCAN [145] in order to build level $i + 1$. The result of H-DBSCAN leads the cluster unit holon to create suitable traffic super-holons at level $i + 1$ (shown by arrow (3)) such that the traffic sub-holons which are in convoy at level i are grouped into a single traffic super-holon at level $i + 1$. The cluster unit holon at level i creates also his own cluster unit super-holon (a cluster unit holon at level $i + 1$) shown by arrow (4). Then traffic sub-holons at level i send their states variables to their respective traffic super-holon at level

$i + 1$ shown by arrow (5). The traffic super-holons uses the states variables of their traffic sub-holons to estimate their own states variables. All the holons at level i become idle (this is made to re-invoke these holons when needed) shown by arrow (6-7), the new current level becomes $i + 1$ and simulation continues at level $i + 1$. The algorithms of both traffic holons and cluster unit holons taking into account transition to upper level case is presented in Section 7.2.4. Note that macro is the highest level: it's not possible to go higher than macro level.

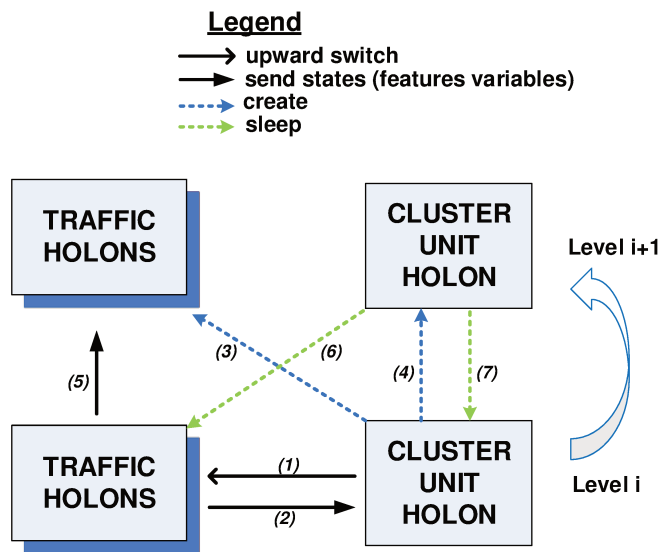


Figure 7.3: Interaction model in transition to coarser representation case

7.2.3/ INTERACTION MODEL BETWEEN HOLONS FOR THE TRANSITION TO LOWER LEVEL

To achieve a transition to lower levels, we assume that all the downward transitions of holarchy are jumps of degree 1 i.e. it is not possible in our model to make a transition for example from level 2 to directly level 0 of the holarchy presented in Figure 6.7 on page 99. To perform such action, two transitions have to be performed: a first transition from level 2 to level 1 and a second transition from level 1 to level 0. If we assume that the current level is level i , transition to lower levels represent a migration from level i to level $i - 1$. This kind of transition involves a more finer representation.

The interactions model between traffic holons and cluster unit holons are depicted by Figure 7.4. Firstly, the cluster unit holon at level i sends a downward switch event to traffic holons at level i as shown by arrow (1). Since all sub-holons at level $i - 1$ are idle, the first step is to reinvoke all the sub-holons shown by arrows (2) and (3). Then each traffic super-holon at level i generates the states variables of its traffic sub-holons throw

probabilistic distribution and sends these states variables to its traffic sub-holons at level $i - 1$ shown by arrow (4). Since the upper levels decrease the accuracy of simulation, they are required only if needed (user needs, lack of computational resources, visualization etc.). Therefore, the upper levels are released when switching to the lower levels which is shown by arrow (5-6). In fact, as much as possible, the simulation tends to be at the lowest possible level. The new current level becomes $i - 1$ and simulation continues at level $i - 1$. The algorithms of both traffic holons and cluster unit holons taking into account switch to lower level case is presented in Section 7.2.4. Note that micro level is the lowest level: it's not possible to go lower than micro level.

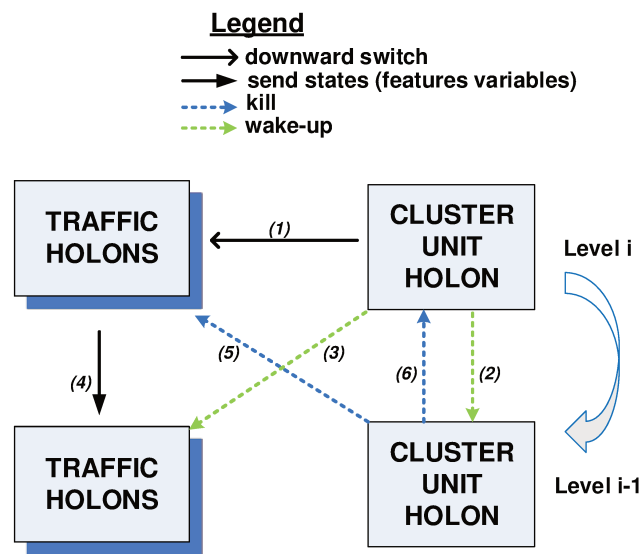


Figure 7.4: Interaction model in transition to finer representation case

7.2.4/ HOLONS BEHAVIOR ALGORITHMS

This section presents the pseudo code of both the traffic holons and cluster unit holons depicting the general behaviors of the holons.

7.2.4.1/ TRAFFIC HOLON ALGORITHM

Algorithm 4 defines the pseudo code of traffic holons at each time step. The three main cases which affect the behavior of the traffic holon as shown above are defined. In fact, lines 3, 4, 5, 7, 8 describe the behavior of traffic holon in transition to the upper level case. Lines 11, 12, 14 describe the behavior of traffic holon in transition to the lower level case and lines 16, 17 describe the behavior of traffic holon in no transition case.

In line 8 of Algorithm 4, traffic holons compute the error of approximation of merging several traffic sub-holons into a traffic super-holon. Perception model in line 16 of Algorithm 4 and update state variables model in line 17 of Algorithm 4 are not defined in this section in order to have a general model.

Algorithm 4 Traffic Holons at current level i (h^i) at each time step

```

1: while Simulation do
2:   if Transition to Upper Level then
3:     Receive upward switch event from  $\mathcal{H}^i$ 
4:     Send states to  $\mathcal{H}^i$ 
5:     Send states to  $h^{i+1}$ 
6:     [New current level becomes  $i + 1$ ]
7:     State estimation of  $h^{i+1}$ 
8:     Compute Approximation Error
9:   else
10:    if Transition to Lower Level then
11:      Receive downward switch event from  $\mathcal{H}^i$ 
12:      Send states to  $h^{i-1}$ 
13:      [New current level becomes  $i - 1$ ]
14:      States estimation of  $h^{i-1}$ 
15:    else ▷ No Transition
16:      Perception: update neighborhood
17:      Update states variables
18:    end if
19:  end if
20: end while

```

7.2.4.2/ CLUSTER UNIT HOLON ALGORITHM

Algorithm 5 defines the pseudo code of cluster unit holon at each time step. The three main cases which affect the behavior of cluster unit holon as shown above are defined. In fact, lines 3, 4, 5, 6, 7, 9 describe the behavior of cluster unit holon in transition to the upper level case. Lines 12, 13, 15 describe the behavior of cluster unit holon in transition to the lower level case and lines 17 describes the behavior of cluster unit holon in no transition case.

7.3/ DYNAMIC MANAGEMENT OF HOLARCHY FOR TRAFFIC SIMULATION

In the previous section, we have presented the general framework allowing a dynamic adaptation of level of detail during simulation. In this section this framework is used for the multilevel simulation of traffic scenarios.

Let us assume that the parameters, which describe the state variables of a given traffic

Algorithm 5 Cluster Unit Holon at current level i (\mathcal{H}^i) at each time step

```

1: while Simulation do
2:   if Transition to Upper Level then
3:     Send upward switch event to  $h^i$ 
4:     Receive states from  $h^i$ 
5:     Apply H-DBSCAN
6:     Create  $h^{i+1}$  based on H-DBSCAN results
7:     Create  $\mathcal{H}^{i+1}$ 
8:     [New current level becomes  $i + 1$ ]
9:     Send sleep request to  $h^i$  and  $\mathcal{H}^i$ 
10:  else
11:    if Transition to Lower Level then
12:      Send downward switch event to  $h^i$ 
13:      Send wake-up request to  $h^{i-1}$  and  $\mathcal{H}^{i-1}$ 
14:      [New current level becomes  $i - 1$ ]
15:      Kill  $h^i$  and  $\mathcal{H}^i$ 
16:    else ▷ No Transition
17:      Monitor the system and check if a transition is needed
18:    end if
19:  end if
20: end while

```

holon h_α are: position x_α , speed v_α , acceleration \dot{v}_α , gap to the preceding vehicle s_α , road lane where traffic holon moves L_α , and vehicle length l_α . Figure 3.2 on page 35 depicts these parameters. In addition, let us assume that w_α is the weight of traffic holon: the number of traffic sub-holons composing a traffic super-holon. For any atomic traffic holon h_α , $w_\alpha = 1$.

In order to present the holonic model for traffic simulation in a real traffic scenarios, the behavior of traffic holons and cluster unit holons need to be defined precisely in the three above cases: no transition, transition to upper and transition to lower level.

7.3.1/ TRAFFIC SIMULATION IN NO TRANSITION CASE

This section defines line 16 and 17 of Algorithm 4. Section 7.3.1.1 defines line 16 and Section 7.3.1.2 defines line 17 of Algorithm 4.

7.3.1.1/ PERCEPTION MODEL: UPDATE NEIGHBORHOOD

Multilevel simulation requires a clear distinguish between the application agent model and the environment model [51] in order to allow independent and specific management of their respective levels of detail. This thesis focuses on the application agent model i.e. on the vehicles and their interactions. Multilevel environment model for traffic simulation based on HMAS has been already proposed on literature [46, 45]. The authors are developed a realistic virtual environment in order to test particular domain-specific procedures.

In their work, the term “environment” corresponds to the concept of “agent environment”. In fact, they proposed an organizational model describing the structure and the dynamics of the environment. The environment is structurally divided into areas, sub-areas, etc. Their proposal specifies the rules for changing the level of detail dynamically. The quality of the approximation between two levels is evaluated with energy-based indicators.

Based on these works, in the road traffic domain, at each time step, a traffic holon h_α can perceive the environment, which leads it to know the position and speed of its preceding traffic holon $h_{\alpha-1}$ given by the environment model. This allows a traffic holon to compute the net gap to its preceding traffic holon s_α and the velocity difference to its preceding traffic holon Δv_α .

7.3.1.2/ BEHAVIORAL MODEL

The acceleration model of traffic holon is based on Intelligent Driver Model (IDM) [147] presented in Section 3.3.1.1. We have chosen IDM because its implementation is easy, results of IDM calibration are available and IDM is widely cited in microscopic traffic simulation. Moreover, IDM tends to be a realistic¹ car-following model. However, our proposal can be used by other car-following models such as GM model [23].

As presented in Chapter 3, the general longitudinal movement of the vehicles can be described by car-following models, which take into account the direct leader and result in expressions for the acceleration function of the form

$$\frac{dv_\alpha}{dt} = f(s_\alpha, v_\alpha, \Delta v_\alpha) \quad (7.1)$$

As the considered acceleration function f is in general nonlinear, we have to solve the set of ordinary differential equations by means of numerical integration. In the context of car-following models, it is natural to use an explicit scheme assuming constant accelerations within each update time interval Δt [68]. This leads to the explicit numerical update rules [69]:

$$\begin{aligned} v_\alpha(t + \Delta t) &= v_\alpha(t) + \dot{v}_\alpha(t)\Delta t, \\ x_\alpha(t + \Delta t) &= x_\alpha(t) + v_\alpha(t)\Delta t + \frac{1}{2}\dot{v}_\alpha(t)(\Delta t)^2 \end{aligned} \quad (7.2)$$

where $\dot{v}_\alpha(t)$ is an abbreviation for the acceleration function $f(s_\alpha(t), v_\alpha(t), \Delta v_\alpha(t))$. For $\Delta t \rightarrow 0$, this scheme locally converges to the exact solution of Eq. 3.5 on page 36 with consistency order 1 for the velocities and consistency order 2 for the positions with respect to the L2-norm [68, 69]. A typical update time interval Δt for the IDM is between 0.1

¹Illustrated on <http://www.traffic-simulation.de>

and 0.2 [69]. Nevertheless, the IDM is approximately numerically stable up to an update interval of $\Delta t \approx T/2$, that is half of the desired time gap parameter T .

Equation 7.2 describes the behavior of each traffic holon (traffic super-holon or traffic sub-holon) used to update its states over time.

7.3.2/ TRAFFIC SIMULATION IN TRANSITION TO UPPER LEVEL CASE

This section defines the lines 7 and 8 of Algorithm 4. Section 7.3.2.2 defines the line 8 of Algorithm 4 and Section 7.3.2.3 defines the line 7 in the same algorithm. Moreover, Section 7.3.2.1 defines the similarity distance between the traffic holons needed to apply H-DBSCAN algorithm as shown at the line 5 of Algorithm 5.

7.3.2.1/ SIMILARITY DISTANCE BETWEEN TRAFFIC HOLONS

To apply H-DBSCAN for the cluster unit holon, a distance metric telling how far traffic holons h_α and $h_{\alpha'}$ are have to be defined. This distance function is based on the value of their respective state variables. In this thesis, Euclidean distance is used. In fact, Euclidean distance fits well with traffic application [78]. The distance between two traffic holons is defined by Equation 7.3.

$$dist(h_\alpha, h_{\alpha'}) = \begin{cases} \sqrt{(x_\alpha - x_{\alpha'})^2 + (v_\alpha - v_{\alpha'})^2}, & \text{if } L_\alpha = L_{\alpha'} \\ +\infty, & \text{else} \end{cases} \quad (7.3)$$

If traffic holons h_α and $h_{\alpha'}$ move on the same lane the distance metric is Euclidean distance. In contrary, if traffic holons h_α and $h_{\alpha'}$ move on different lanes, the distance metric tends towards infinity. In fact, we assume that there is no direct interaction between lanes in the context of grouping.

7.3.2.2/ MULTILEVEL INDICATORS

As stated before, complexity leads to compromise [109, 51]. An accurate simulation at micro level needs a high computational cost while simulation at upper levels carries out a coarse behavior with an acceptable computational cost. In our model, simulation can migrate to a coarser representation or to a finer representation and vice-versa knowing that finer representation is the most desired. Since we consider different levels of detail within the same model, the transition issue between these levels becomes crucial [51]. Upper levels decrease the precision of simulation, therefore involving them require to

quantify the approximation error. This action is done by multilevel indicator in HMAS [46, 45].

The multilevel indicator in this thesis is based on standard deviation. Standard deviation is a statistical concept used to measure the dispersion of a dataset. On the one hand, lower is the standard deviation value; and higher is the quality of the data grouping: the data are sensibly homogeneous. On the other hand, higher is the standard deviation value; and lower is the quality of the data grouping: the data seems to be heterogeneous.

In this thesis, standard deviation is used for verifying the homogeneity of the sub-holons within their super-holon. The low value of standard deviation means that sub-holons are homogeneous and their grouping into a super-holon seems to be acceptable. In contrary, the high value of standard deviation means that sub-holons are heterogeneous and their grouping into a super-holon seems to be worse.

Standard deviation is applied on two states variables of traffic holons:

- on the speed state variable named speed standard deviation. The speed standard deviation of traffic holon h_α is noted σ_α^{spd} . Speed standard deviation measures the dispersion of several traffic sub-holons speed. Note that for any atomic traffic holon h_α , $\sigma_\alpha^{spd} = 0$. Speed standard deviation is defined by Eq. 7.9 on page 115.
- on the interdistance state variable named gap standard deviation. The gap standard deviation of traffic holon h_α is noted σ_α^{gap} . Gap standard deviation measures the dispersion of traffic sub-holons interdistance. Note that for any atomic traffic holon h_α , $\sigma_\alpha^{gap} = 0$. Gap standard deviation is defined by Eq. 7.10 on page 115.

7.3.2.3/ STATES ESTIMATION FROM LOWER TO UPPER LEVELS

Let h a traffic super-holon which has n traffic sub-holons $h_\alpha, \alpha = 1, \dots, n$. α indices are ordered such that $(\alpha - 1)$ denote the preceding traffic holon. For the following, we assume that variables with indices are for traffic sub-holons and variables without indices are for traffic super-holon.

States variables of a traffic super-holon h are estimated from the states of its traffic sub-holons $h_\alpha, \alpha = 1, \dots, n$ by the Eq. 7.4 – 7.10. The speed v , length l , position x , weight w , standard deviation σ^{spd} and σ^{gap} of the super-holon h is given by:

- **Speed:** Speed of a traffic super-holon, given by Eq. 7.4 is the mean of speed of its traffic sub-holons.

$$v = \frac{1}{n} \sum_{\alpha=1}^n v_\alpha \quad (7.4)$$

- **Position:** Position of a traffic super-holon, given by Eq. 7.5 is the position of the traffic sub-holon which precedes all the other traffic sub-holons.

$$x = x_1 \quad (7.5)$$

- **Lane:** Lane of a traffic super-holon, given by Eq. 7.6 is the same lane of all its traffic sub-holons.

$$L = L_\alpha, \alpha = 1, \dots, n \quad (7.6)$$

- **Length:** Length of a traffic super-holon, given by Eq. 7.7 is the aggregate length of all its traffic sub-holons including gap between them.

$$l = \sum_{\alpha=1}^n l_\alpha + \sum_{\alpha=1}^{n-1} s_\alpha \quad (7.7)$$

- **Weight:** Weight of a traffic super-holon, given by Eq. 7.8 is sum of the weight of its traffic sub-holons.

$$w = \sum_{\alpha=1}^n w_\alpha \quad (7.8)$$

- **Speed standard deviation:** Speed standard deviation, given by Eq. 7.9 measures the dispersion of the speed of sub-holons.

$$\begin{aligned} \sigma^{speed} &= \sqrt{\frac{1}{n} \sum_{\alpha=1}^n (v_\alpha - \mu^{speed})^2} \\ \mu^{speed} &= v = \frac{1}{n} \sum_{\alpha=1}^n v_\alpha \end{aligned} \quad (7.9)$$

- **Gap standard deviation:** Gap standard deviation, given by Eq. 7.10 measures the dispersion of the inter-distance between sub-holons.

$$\begin{aligned} \sigma^{gap} &= \sqrt{\frac{1}{n-1} \sum_{\alpha=1}^{n-1} (s_\alpha - \mu^{gap})^2} \\ \mu^{gap} &= 1/(n-1) \sum_{\alpha=1}^{n-1} s_\alpha \end{aligned} \quad (7.10)$$

7.3.3/ TRAFFIC SIMULATION IN TRANSITION TO LOWER LEVEL CASE

This section defines line 14 of Algorithm 4. It presents the means for traffic sub-holons to estimate their states from the state of their traffic super-holon. To this end, states variables of traffic sub-holons $h_\alpha, \alpha = 1, \dots, n$ are generated from the states of their traffic super-holon h . Speed v_α , length l_α , position x_α , weight w_α of the traffic sub-holons $h_\alpha, \alpha = 1, \dots, n$ are given by:

- **Speeds:** We assume that speeds of traffic sub-holons within their super-holon follow a normal distribution with mean μ^{speed} and standard deviation σ^{speed} . In order to generate the speeds of traffic sub-holons based on the speed and the speed standard deviation of traffic super-holon, the model uses Box-Muller method [12]. Box-Muller transform is a pseudo-random number sampling method for generating pairs of independent, standard and normally distributed random numbers. Standard Box-Muller transform generates values from the standard normal distribution $\mathcal{N}(0, 1)$. From the $\mathcal{N}(0, 1)$, we can deduce $\mathcal{N}(\mu^{speed}, (\sigma^{speed})^2)$ such that if $X \sim \mathcal{N}(0, 1)$ and $Z = \mu^{speed} + \sigma^{speed}X$ then $Z \sim \mathcal{N}(\mu^{speed}, (\sigma^{speed})^2)$. The speeds $v_{\alpha, \alpha=1, \dots, n}$ of traffic sub-holons are given by Eq. 7.11.

$$v_{\alpha, \alpha=1, \dots, n} = \mu^{speed} + \sigma^{speed} \text{Box-Muller}(0, 1) \quad (7.11)$$

- **Positions:** We assume that the gaps between traffic sub-holons within their super-holon follow a normal distribution with mean μ^{gap} and standard deviation σ^{gap} . Positions of traffic sub-holons $x_{\alpha, \alpha=1, \dots, n}$ are given by Eq. 7.12.

$$\begin{cases} x_1 = x \\ x_{\alpha, \alpha=2, \dots, n} = x_{\alpha-1} - l_{\alpha-1} - s_{\alpha} \end{cases} \quad (7.12)$$

With $s_{\alpha} = \mu^{gap} + \sigma^{gap} \text{Box-Muller}(0, 1)$

- **Lanes:** Lane of the traffic sub-holons $L_{\alpha, \alpha=1, \dots, n}$ is the same lane of their traffic super-holon as in Eq. 7.13.

$$L_{\alpha, \alpha=1, \dots, n} = L \quad (7.13)$$

- **Length, weight:** of a traffic sub-holons remain the same before switching to upper levels.

7.4/ DISCUSSION

As stated in Chapter 5, any multilevel model of traffic need to satisfy Constraint 1 related to compatibility, and Constraint 2 related to conservation [11]. On the first hand, compatibility constraint means the multilevel simulation have to allow a transition from one level of detail to another because the levels of detail combined have neither the same time nor the space scale. On the other hand, conservation constraint means that no vehicle should be lost when making a transition from one level of detail to another in the multilevel simulation of traffic. One question is therefore how these constraints are satisfied:

- **Regarding constraint 1:** In our holonic and dynamic multilevel model of traffic, compatibility constraint is satisfied by the methodologies proposed in Section 7.2 and Section 7.3. These sections present how to dynamically make a transition from one representation to another.
- **Regarding constraint 2:** Conservation constraint is managed in our holonic and dynamic multilevel model of traffic by the state variable weight of the traffic holons. In fact, each traffic super-holon knows the exact number of traffic sub-holons in his inner context. This help each traffic super-holon to generates the exact number of its sub-holons when going down in holarchy i.e. when retrieving sub-holons. In order words, this guarantee that no vehicle is lose when migrating both in upper and lower levels. Furthermore standard deviation helps to measure the homogeneity of several traffic sub-holons within their traffic super-holon. In fact, the smaller the value of σ^{gap} and σ^{speed} , the more the grouping into a traffic super-holon is acceptable.

7.5/ CONCLUSION

This chapter presents a methodology for the dynamic multilevel simulation of traffic. The proposal is based on a holonic architecture made by a set of recursive holons which structure the traffic system. The holarchy provides the useful support for setting up the level change mechanisms and for dynamically modulating the complexity of the behaviors of a simulation.

In summary, the contributions of this chapter are: (i) a holonic model for dynamic management of the holarchy of traffic. This contribution enables the dynamic adaptation of the level of detail of the simulated holarchy. (ii) a definition of a multilevel indicator. This contribution enables to measure the consistency of the transition process.

Several research questions have been investigated in this chapter:

- Regarding RQ2 related to the holonification methodology, this chapter has completed the upward and downward methodology presented in chapter 6 to structure the holarchy. In fact, an event-based methodology allowing a dynamic transition between different levels of detail was presented as well as the interactions models between the holons of the system.
- Regarding RQ4 related to multilevel indicator used to evaluate the gap between two adjacent levels of detail. We have proposed standard deviation. This indicator attempts to provide a response to the evaluation of the consistency of a multilevel simulation. In fact, the multilevel indicator tries to define the difference between

the simulation results of the level considered during the simulation and those of the most precise level.

- Constraint 1 related to compatibility and constraint 2 related to conservation are tackled by the holonic and dynamic multilevel of traffic.

Figure 7.5 summarizes this chapter. In fact, the works presented in this chapter can be considered as model for the design of a multilevel simulation of traffic, and need to be instantiated by a particular traffic scenario. In the next chapter, the proposal will be tested on several traffic scenarios.

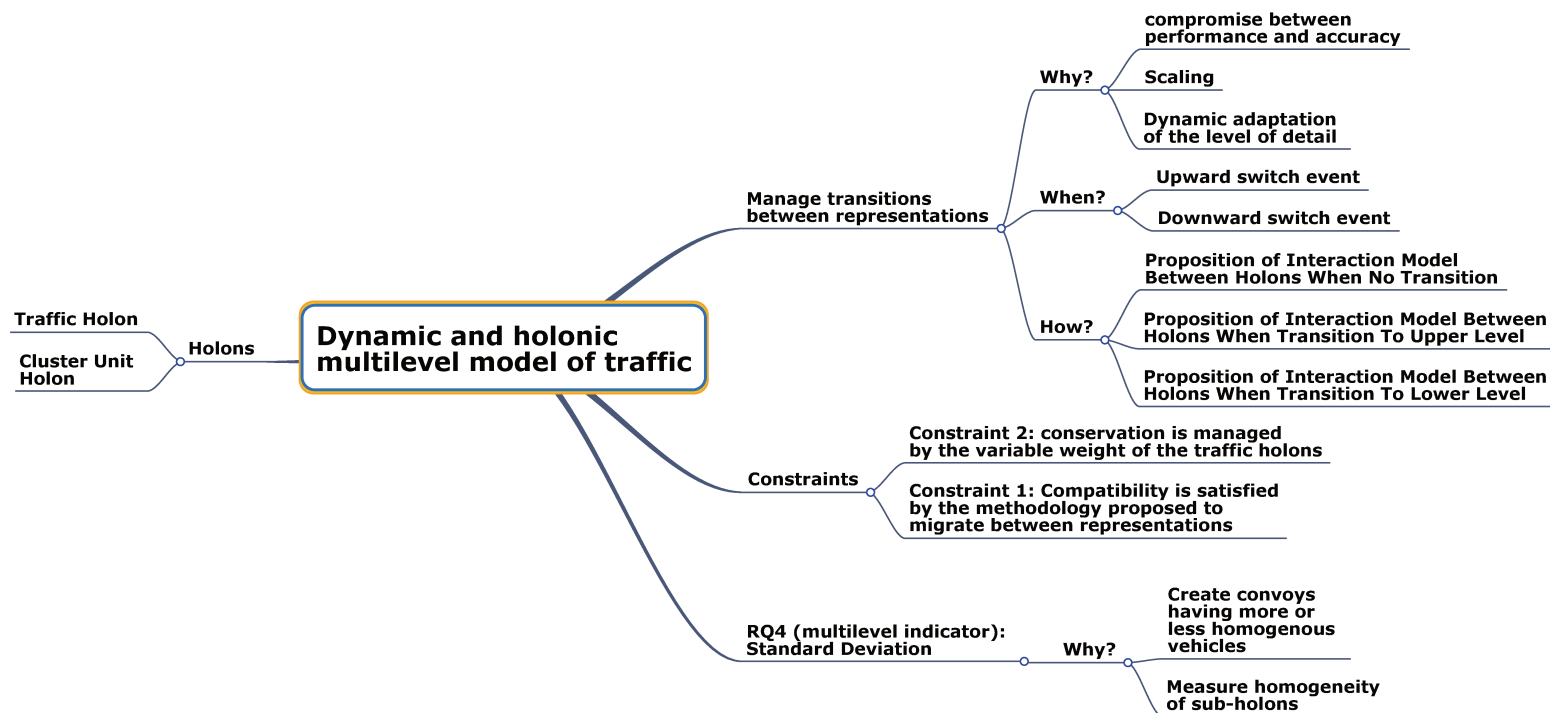


Figure 7.5: Summary of the dynamic and holonic multilevel model of traffic

APPLICATION TO HIGHWAY SIMULATION

8.1/ INTRODUCTION

In the previous chapters, a holonic and dynamic multilevel model of traffic is presented. In fact, a methodology allowing a dynamic adaptation of the level of detail of the simulated entities is presented. The multilevel model of the traffic system integrates the different levels of detail exhibited by traffic system (individual vehicles, convoys, convoy of convoys, etc.). Following this methodology, the goal of this chapter is to present an implementation of the multilevel simulation model described in the previous chapters on a concrete application case. To this end, this thesis focuses on highway's simulation. In fact, highway is a widely used application case for multilevel modeling and simulation [84]. Moreover, coarse representations (mesoscopic and macroscopic) fit well with highway topology network [136, 18].

The model proposed and described in this chapter is part of a larger effort within the laboratory CIAD¹ (Connaissance et Intelligence Artificielle Distribuées) aiming at providing a software environment for simulating the dynamics of a city and the different modes of transport: pedestrians [51], drones [100], carpooling [63, 46], bicycles [15], etc. This chapter deals with the case of road traffic, but the models are not intended to be used for this purpose only, and could be extended to other types of entities.

This chapter is structured as follows: Section 8.2 presents the tools used for experimentation. Section 8.3 presents an execution of our dynamic and multilevel model of traffic on a small case study. A comparison of the results between our proposal and microscopic model is given. Section 8.4 presents the performances of the models proposed in the thesis. Moreover, a comparison between the proposal and microscopic model is also highlighted. Section 8.5 makes a discussion on the proposal and finally, Section 8.6

¹<http://www.ciad-lab.fr/>

concludes this chapter.

8.2/ EXPERIMENTATION TOOLS

In order to experiment the propositions presented in previous chapters, the SARL² programming language coupled with the Janus³ execution platform are used in this thesis. These tools were selected for several reasons. Firstly, they fully support holonic architecture, i.e. they are capable to implement and execute recursive hierarchical systems. Moreover, these tools are free, open source, and documentation is available on Internet. Finally, the community of these tools is increasing: the year 2020 will house the 4th international workshop⁴ dedicated to these tools. The following presents them.

8.2.1/ SARL

SARL is a general statically-typed agent-programming language [120]. SARL aims at providing the fundamental abstractions for dealing with concurrency, decentralization, distribution, interaction, reactivity, autonomy and dynamic reconfiguration. The first definition of SARL was proposed in 2014 by Rodriguez et al. [120]. The initial metamodel of SARL was defined between 2010 and 2014 and known as the Capacity-Role-Interaction-Organization metamodel [50].

The main perspective that guided the creation of SARL is the establishment of an open and easily-extensible language. SARL can be used for agent-based simulations because SARL provides characteristics for agent execution and direct communication. The specificity of SARL is that agents are true holons. This specificity allows to SARL to provide a complete support for the development of HMAS.

A SARL Run-time Environment (SRE) executes or interprets compiled SARL code on an “hardware platform”. Figure 8.1 presents the SARL compilation process of a SARL program in which the run-time environment is involved.

SARL compilation process involve three main components:

- SARL Compiler: The SARL compiler transforms the source SARL language into the target language. Several target languages may be considered by this compiler. Because most of the agent frameworks are written in Java, the SARL compiler targets this object-oriented programming language by default. The SARL compiler translates SARL statements into their object-oriented equivalent statements. Three

²<http://www.sarl.io>

³<http://www.janusproject.io>

⁴<http://www.multiagent.fr/Conferences:SARL20>

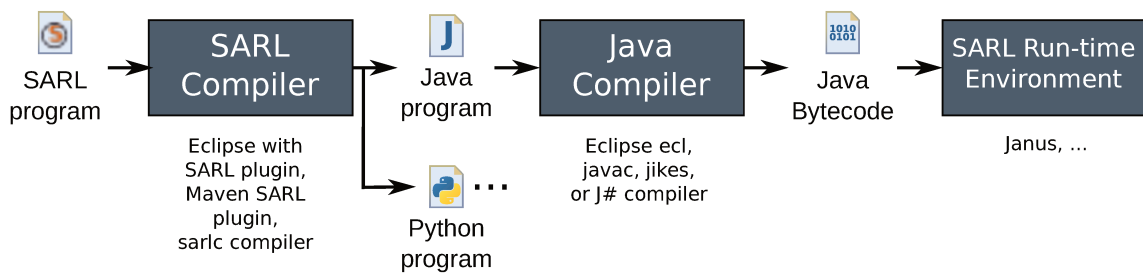


Figure 8.1: SARL Compilation Process [47]

different implementations of the SARL compiler are provided: a specific command-line tool (sarlc), the Eclipse development environment plug-in, and a Maven plug-in.

- **Java Compiler:** The files generated by the SARL compiler when it is using the Java generator are standard Java's files. They must be compiled with one of the compilation tools that are available: Eclipse's ecl, Oracle's javac, IBM's jikes... The result from the Java compilation is a collection of binary files that may be run by a virtual machine.
- **SARL Run-time Environment:** The SARL Run-time Environment (SRE) is a collection of tools that enables the run of an agent-based application written with SARL. Such SRE must implement each service and feature that are assumed to be provided by the run-time environment. When the target platform is Java-based, the SRE is composed by a standard Java Runtime Environment (JRE), and the Janus Java library, which provides the base classes for running agents written with SARL. In this latest example, a command-line tool is provided for launching the Janus platform: janus.

8.2.2/ JANUS

Janus platform was initially published during the 2007-2008 period. Since 2014, Janus is fully reimplemented to support the SARL Agent-Oriented Programming Language. Janus is the default SARL Run-time Environment. The role of Janus is to provide all the libraries and plugins that are needed for running SARL agents. Janus is an open-source multi-agent platform fully implemented in Java. Janus enables developers to quickly create web, enterprise and desktop multiagent-based applications. It provides a comprehensive set of features to develop, run, display and monitor multiagent-based applications. Janus-based applications can be distributed across a network. Janus could be used as an agent-oriented platform, an organizational platform, and/or an holonic platform. It also natively manages the concept of recursive agents and holons.

8.3/ CASE STUDY

The goal of this section is to present the execution of the holonic and dynamic multilevel model described in the previous chapters on a concrete traffic scenario.

Let us remind that, traffic can be modeled and simulated according to several perspectives, i.e. microscopically, mesoscopically or macroscopically. Macroscopic models of traffic could be easy to implement and instantiate. However, the accuracy of the results of this type of simulation remains limited [64]. In contrary, microscopic models of traffic exhibit the most accurate behavior. However, the scalability of this type of simulation remains limited [51]. In order to take into account the benefits of both macroscopic, mesoscopic and microscopic model, a multilevel approach can be used [84]. In fact, multilevel model of traffic is a suitable approach to deal with the compromise between simulation accuracy and the availability of computational resources [16, 11, 51, 45]. According to Oxford dictionary, a compromise is an intermediate state between conflicting alternatives reached by mutual concession. In scientific community, the notion of compromise depends on the application domains [114]. For example, in the context of multiagent optimisation problems, the notion of compromise solution refers to equity or fairness [59]. In the context of optimisation under multiple scenarios, compromise solutions refer to the idea of robustness [72]. In the case of multilevel modeling and simulation, compromise refers to the suitable choice of the representation to simulate the system source leading to produce an intermediate results between accuracy of the simulation and computational load [51], etc.

This thesis focuses on multilevel modeling and simulation, thus, compromise refers to the choice of the representation to simulate the system. In fact, a compromise between simulation accuracy and availability of computational resources means that the multilevel models of traffic produces intermediate results between accuracy and computational load. This also means that multilevel models of traffic optimize the loose of accuracy and the computational gain.

In order to [evaluate the loose of accuracy and the gain of computational resource](#) in our dynamic and holonic multilevel model of traffic, a small initial case study composed by two scenarios is defined as outlined by Figure 8.2. In Scenario 1, simulation is done only at level 0, i.e. at the microscopic level from point A to D. In Scenario 2, from A to B simulation is done at level 0, from B to C simulation is done at level 1, and from C to D simulation is done at level 0. To enable a dynamic transition from level 0 to level 1, a threshold of the processor load is defined for each experiment. This processor load threshold allows a dynamic migration from from level 0 to level 1 of scenario 2.

The goal of the case study is to compare results at point D between Scenario 1 and Scenario 2. To this end, 30 vehicles with Intelligent Driver Model (IDM) parameters defined

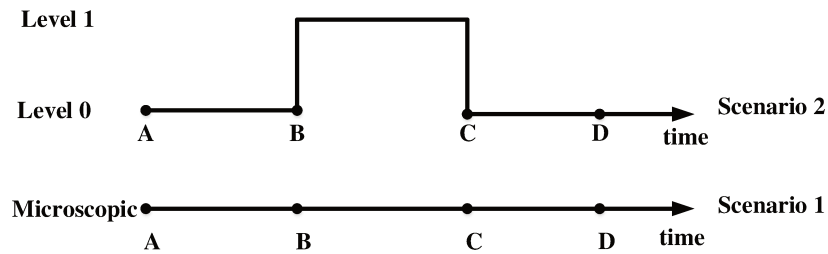


Figure 8.2: Initial case study: execution scenarios on two levels of detail

by Kesting et al. [69] are used such that vehicle 1 follows vehicle 30.

8.3.1/ RESULTS FROM A TO B

From A to B, the two scenarios produce the same results as shown on Figure 8.3. This figure depicts 30 curves for the 30 vehicles with accordion effect. Each curve presents the motion of one vehicle. Time of simulation is on x-axis and positions of vehicles are on y-axis.

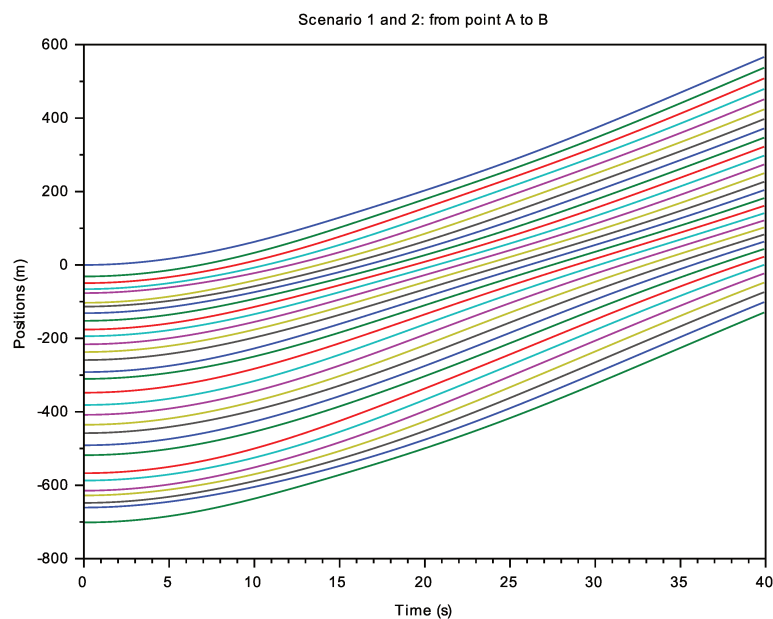


Figure 8.3: Scenario 1 and 2: from A to B

8.3.2/ RESULTS FROM B TO C

From B to C. Scenario 1 produces the results shown on Figure 8.4 and Scenario 2 produces the results shown on Figure 8.5. While Figure 8.4 depicts 30 curves for the 30 vehicles, Figure 8.5 depicts 13 curves for the 13 super-vehicles such that one super-vehicle is composed of 18 sub-vehicles and the other super-vehicles are each composed of one sub-vehicle.

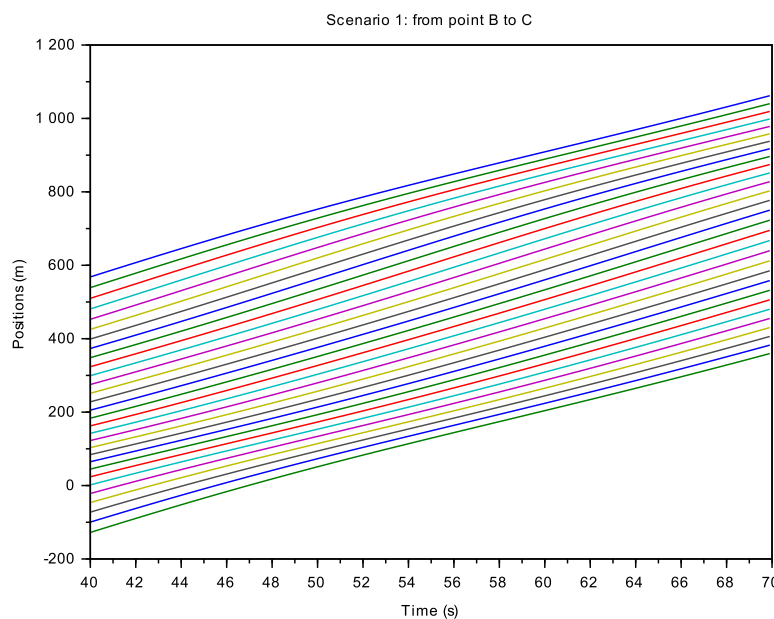


Figure 8.4: Scenario 1: from B to C

8.3.3/ RESULTS FROM C TO D

From C to D, scenario 1 produces the results shown on Figure 8.6. From C to D scenario 2 produces the results shown on Figure 8.7. Figures 8.6 and 8.7 are different that means the results of scenario 1 and scenario 2 at point D are different.

8.3.4/ EVALUATION OF COMPROMISE SIMULATION ACCURACY/AVAILABILITY OF COMPUTATIONAL RESOURCE

This section evaluates the resulted differences between scenario 1 and scenario 2 at point D. On one hand, Figure 8.8 outlines a loss of accuracy of scenario 2 compared to scenario 1. Chart diagrams in blue correspond to the distance traveled by each vehicle in scenario 1. Charts diagram in orange correspond to the difference between distance traveled between scenario 1 and scenario 2. As shown by Figure 8.8 the curves of vehicles in

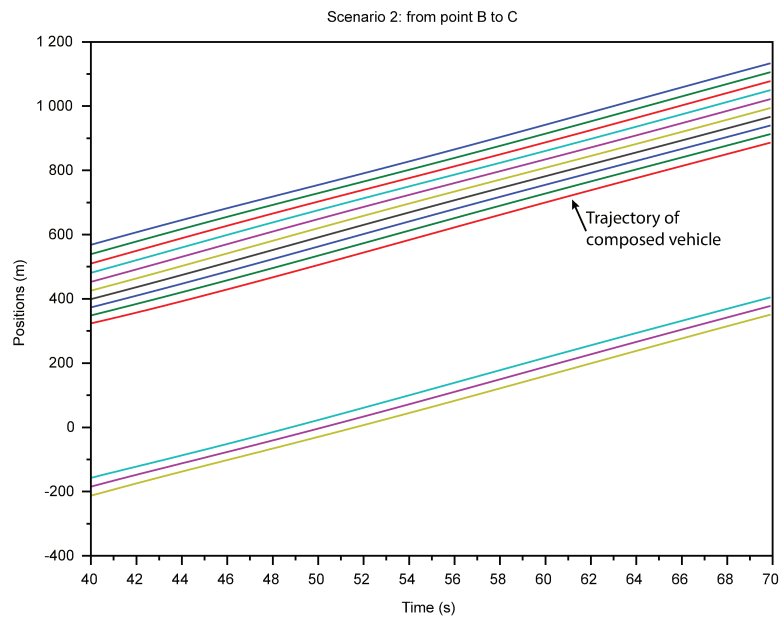


Figure 8.5: Scenario 2: from B to C

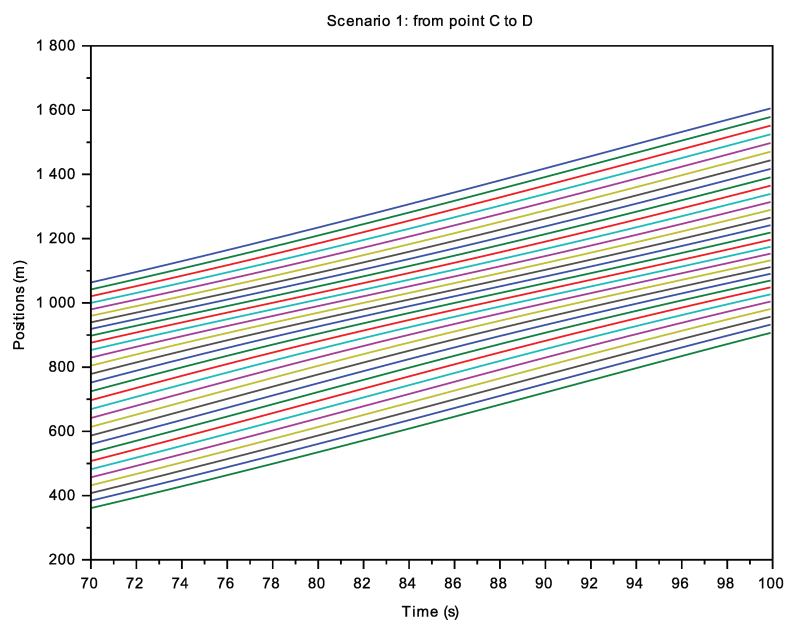


Figure 8.6: Scenario 1: from C to D

scenario 2 have a delay on the distance traveled. There is therefore a loss of accuracy of scenario 2 (multilevel model) compared to scenario 1 (fully microscopic model). The maximum loss of accuracy is 05.87% of distance traveled.

In the other hand, Figure 8.9 presents the save of computational cost of scenario 2 com-

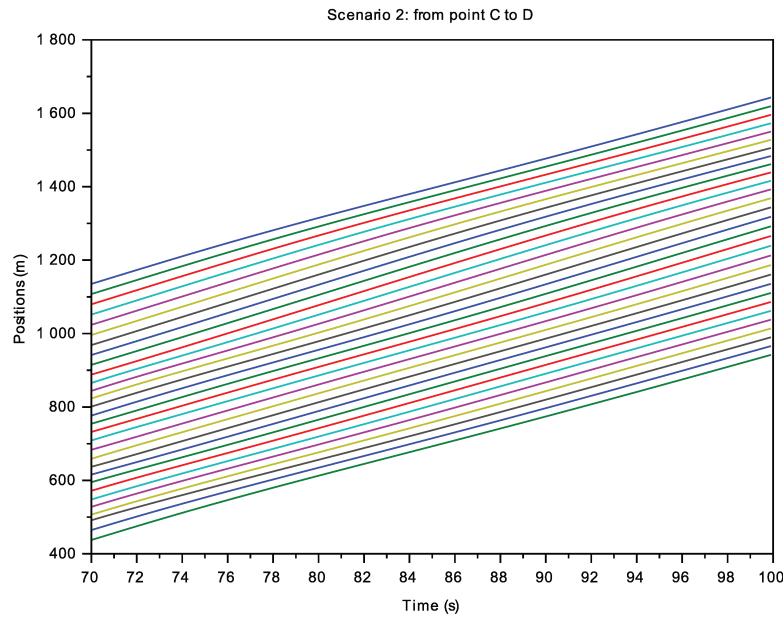


Figure 8.7: Scenario 2: from C to D

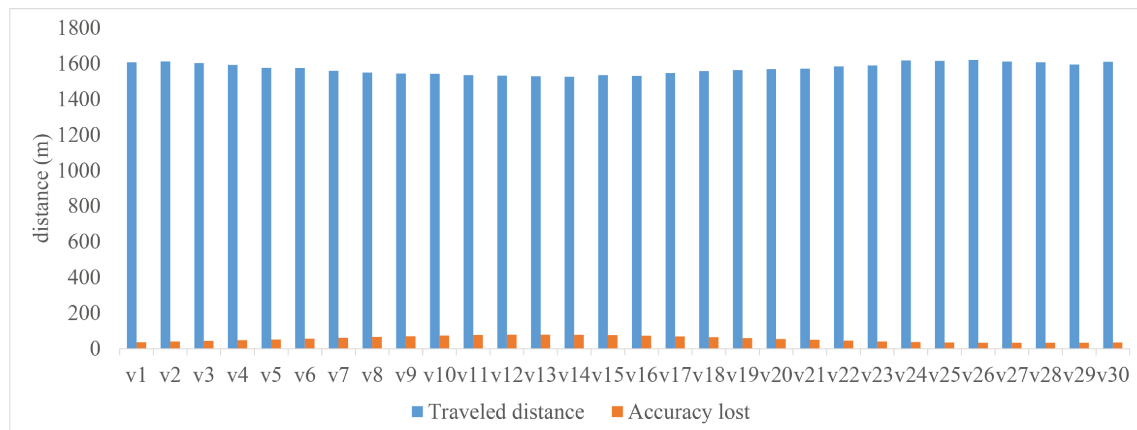


Figure 8.8: Evaluation of accuracy lost by scenario 2

pared to scenario 1. Chart diagram in blue correspond to the overall computational time of scenario 1. Charts diagram in orange correspond to the difference between scenario 1 and scenario 2 of the overall computational time. There is a gain of computational time about of 22.87% for scenario 2.

The maximum loss of accuracy is 05.87% and the save of computational cost is about 22.87% of time execution of the scenario 2 (multilevel model). This means that while the save of the computational cost of the simulation is made, in the same time there is a lost of accuracy of the simulated entities.

Now let's modify the initial case study as presented by Figure 8.10 in order to have three

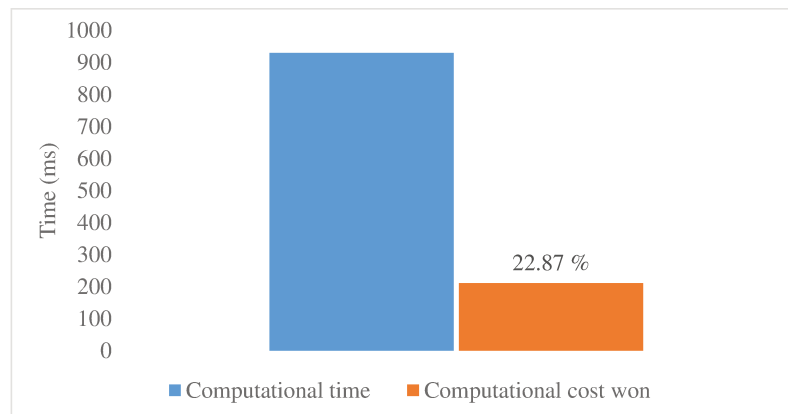


Figure 8.9: Evaluation of computational cost won by scenario 2

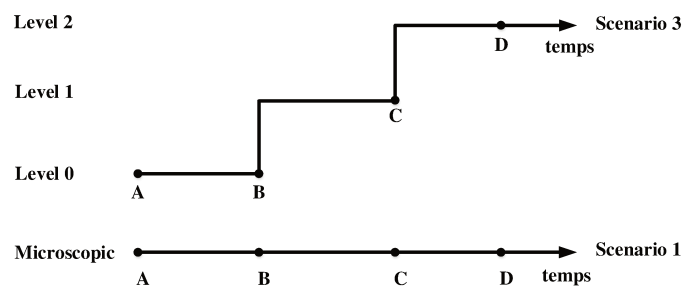


Figure 8.10: Modified case study: executions scenarios on three levels of detail

levels of detail. Scenario 1 has not changed, i.e. scenario 1 is the same on both Figures 8.10 and 8.2. Scenario 3 of Figure 8.10 is a little modification of scenario 2 of Figure 8.2 from C to D only. In contrary to scenario 2 of Figure 8.2, scenario 3 of Figure 8.10 involves three levels of detail. Let's evaluate the resulted differences between scenario 1 and scenario 3 at point D. In one hand, Figure 8.11 outlines a loss of accuracy of scenario 3 compared to scenario 1. Chart diagrams in blue correspond to the distance traveled by each vehicle in scenario 1. Charts diagram in orange correspond to the difference between distance traveled between scenario 1 and scenario 3.

As shown by Figure 8.11 the curves of vehicles in scenario 3 have a delay on the distance traveled. There is therefore a loss of accuracy of scenario 3 compared to scenario 1. The maximum loss of accuracy is 12.71% of distance traveled. We can notice that the maximum loss of accuracy has increased i.e. the maximum loss of accuracy has increased from 05.87% in scenario 2 to 12.71% in scenario 3. Therefore there is an increase of the

loss of accuracy while we go up to the holarchy.

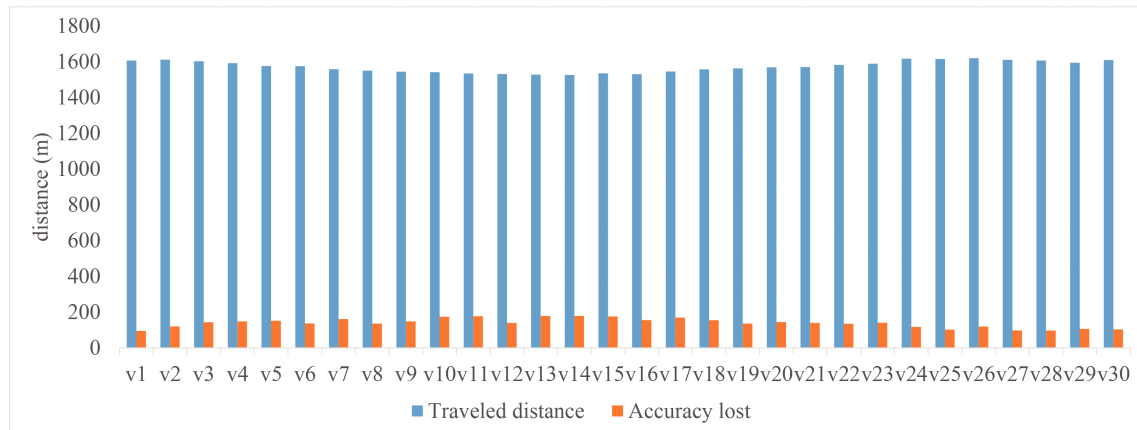


Figure 8.11: Evaluation of accuracy lost by scenario 3

In the other hand, Figure 8.12 presents the save of computational cost of scenario 3 compared to scenario 1. Chart diagram in blue correspond to the overall computational time of scenario 1. Charts diagram in orange correspond to the difference between scenario 1 and scenario 3 of the overall computational time. There is a gain of computational time about of 39.29% for scenario 3. We can notice that the save of the computational cost has increased i.e. the save of the computational cost has increased from 22.87% in scenario 2 to 39.29% in scenario 3. Therefore there is an increase of the save of the computational cost while we go up to the holarchy.

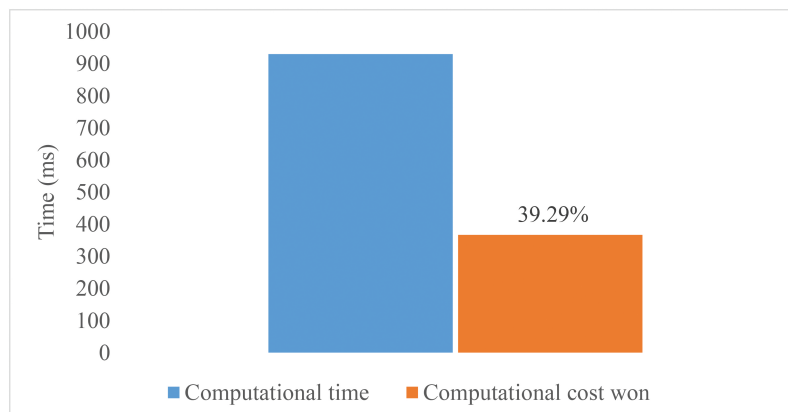


Figure 8.12: Evaluation of computational cost won by scenario 3

In summary, in one hand, the small case study shows that the more, the upper levels are involved, the more the accuracy of simulation decreases. In the other hand, the same case study shows that the more, the upper levels are involved, the more the save of computational resources increases. Therefore, the proposal seems to be suitable to deal with large scale traffic because the proposal can involves upper levels to save the computational cost when needed, i.e., lack of computational resources, visualisation etc. Further experimentation's is presented by the following.

8.4/ THE PERFORMANCE OF THE PROPOSALS

Two mains contributions were proposed in this thesis: the algorithm H-DBSCAN used to cluster homogeneous vehicles and the dynamic management of the holarchy of traffic over time. The performances of these contributions with more vehicles are presented below. The previous case study is made on 30 vehicles. In this section, we provide results with more vehicles.

8.4.1/ H-DBSCAN PERFORMANCE

Figure 8.13 presents the performance of the H-DBSCAN execution with three traffic conditions named traffic distribution 1, traffic distribution 2 and traffic distribution 3. The time execution is made on a dual core laptop with 1.2 Ghz and 2 Go of RAM with 30 runs. The states variables of the vehicles in these three traffic distributions case were generated for running the model.

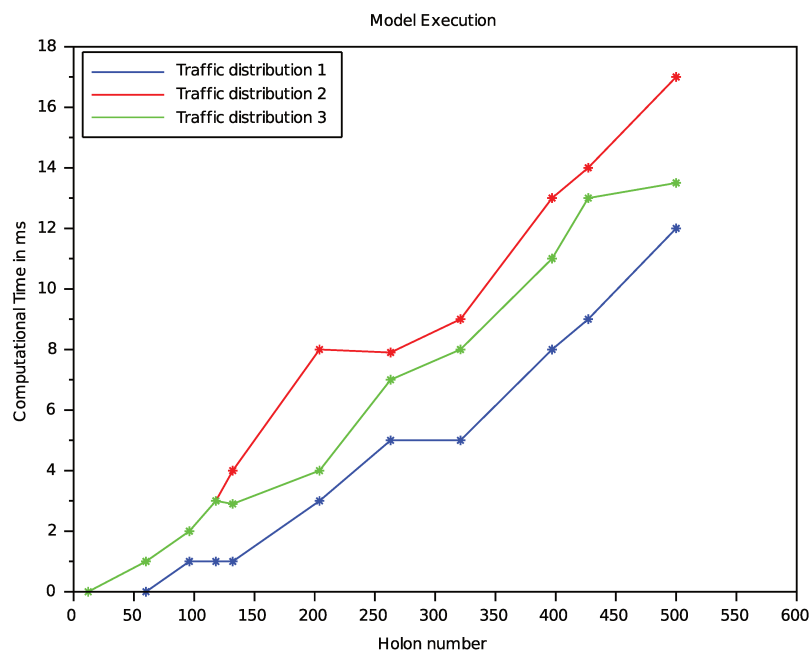


Figure 8.13: H-DBSCAN performances

All the traffic distributions presented in Figure 8.13 seem to outlines the linear execution time. For example, the corresponding linear regression line, which approximate traffic distribution 2 has the following equation: $y = 0.0346x - 0.798$. We assert that H-DBSCAN has a good performance, because the slope of the linear regression of the all the three traffic distributions case tends to zero.

8.4.2/ HOLARCHY MANAGEMENT PERFORMANCE

To evaluate the performance of the model, we will generalize the comparison of scenario 1 and scenario 2 outlined by Figure 8.2 in order to evaluate the rate of accuracy loss and the rate of computational save by more than 30 vehicles. To this end, Figure 8.14 presents the difference between the computational time of Scenario 1 and 2 for more than 30 vehicles taking into account the following constraint: the maximal loss of accuracy of scenario 2 compared to scenario 1 must be less than 10%. In Figure 8.14, the curve in blue represents the computational time of Scenario 1, while the curve in orange represent the computational time of Scenario 2. The save of computational cost is between 20% and 42% for Scenario 2. Moreover, we observe that the more vehicles there are, the more the computational gain increases. Our explanation is that the more the vehicles are, the more the proposal optimizes the compromise accuracy/computational resource leading the proposal suitable for large-scale traffic. Indeed, the high rate of the saved computational cost compared to the low rate of loss accuracy makes our dynamic multilevel very interesting approach to deal with large-scale road traffic modeling and simulation.

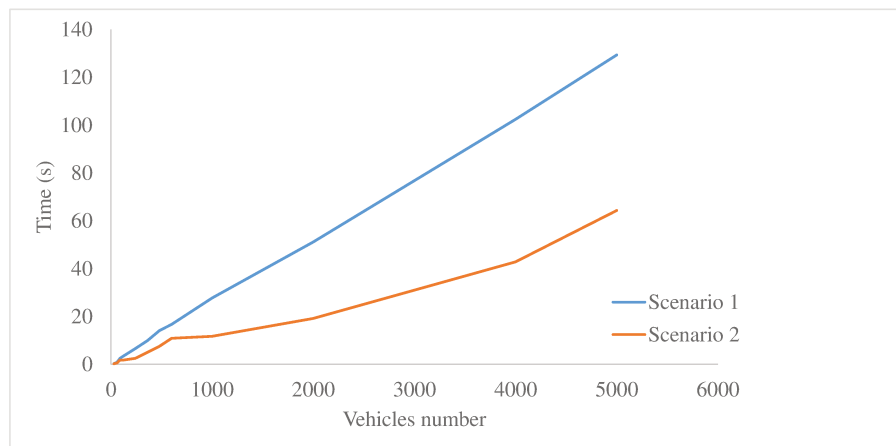


Figure 8.14: Model Performance

8.5/ DISCUSSION

One drawback on this work is that it produces some inconsistent results when traffic is very fluid. However, when traffic is over-congested, i.e. when vehicles are crowded on all sides in front, behind, left and right as presented by Figure 2.2, it produces very interesting results. Therefore, in real life traffic, our multilevel model can be applied successfully as follows: the coarse representation in the sections where traffic is very congested and fine representation where traffic is fluid. In fact these situations are regularly observed in real traffic. Congestion for example, is a recurring phenomenon within traffic flow. TomTom⁵ in its report of 2013 states that in cities like Moscow, Rio de Janeiro, Mexico City, Istanbul and Beijing, people on average spend $> 75\%$ extra time traveling due to traffic. Moreover, Texas Transportation Institute, which conducts a survey of traffic congestion in US states, in its 2009 report, that in 2007 congestion caused an estimated 4.2 billion hours of travel delay. Moreover, congestion brings out the group of vehicles particularly on peak hours [65].

8.6/ CONCLUSION

This chapter presents the multilevel simulation of traffic on highway by a HMAS. Firstly, in this chapter, a case study composed by thirty vehicles was step by step simulated in order to evaluate the outcomes of the compromise between simulation accuracy and the availability of computational resources on two scenarios. The results of our model (scenario 2) show both a gain of computational load and a lost of accuracy of the simulation. The maximum lost of accuracy is 05.87% while the overall gain of computational cost is 22.87%. Secondly, the case study was modified in order to have more than two levels of details in the simulation. The outcomes reveal that: (i) the more the upper levels are involved, the more the computational save increase, (ii) the more the upper levels are involved, the more there are a lost accuracy. In summary, the outcomes of the case study show an interesting balance between the accuracy lost and the computational cost saved.

In the same vein, we have extended the case study made of thirty vehicles to more vehicles, up to five thousands and the outcomes show also an interesting balance between the accuracy lost and the computational cost saved. This leads to the scalability of traffic system as well to represent it from several perspectives.

Furthermore, RQ4 related to multilevel indicator is used to evaluate the gap between two adjacent levels of detail.

To conclude this chapter, let us remind the hypothesis made for this thesis : HMAS is

⁵TomTom is a leading company that produces traffic navigation products.

a suitable paradigm for dynamic multilevel modeling and simulation of large-scale road traffic. The multilevel proposed is:

1. based on HMAS,
2. dynamic (transitions between different levels of detail are dynamics), and
3. scalable (deals with large-scale traffic by managing a compromise between simulation accuracy and availability of computational resources).

The conclusion is therefore that the hypothesis made according to our problematic is validated because the proposal is a dynamic multilevel modeling and simulation of large-scale road traffic by HMAS.



CONCLUSION AND PERSPECTIVES

GENERAL CONCLUSION

9.1/ SUMMARY OF THE CONTRIBUTIONS

Throughout this thesis, we have proposed a multilevel model for large-scale traffic simulation. Traffic system is seen as a system composed by a large number of interacting entities with non trivial graph of interactions whose global dynamic cannot be reduced to the sum of the behaviors of its entities. We find in this vision the characteristics of a large-scale complex system. Typically, these systems exhibit hierarchical structures and self-organizing processes. Due to the complexity exhibited by a traffic system, a multilevel modeling and simulation is therefore suitable to represent it from several perspectives.

The literature review revealed that HMAS is an interesting approach for multilevel simulation of large-scale complex systems. In fact, HMAS allows to represent complex systems by considering several levels of detail (microscopic, mesoscopic and macroscopic). At the bottom of the holarchy is the finest representation, while at the top of the holarchy is the coarsest representation. HMAS allows to decompose a complex system level by level and this decomposition process bring out the hierarchy of the system.

Firstly, multilevel simulation is suitable to represent large-scale traffic from several perspectives. HMAS is also a suitable paradigm to deal with multilevel simulation of complex hierarchical system. These two points leads us to make the hypothesis of this thesis : HMAS is a suitable paradigm for multilevel modeling and simulation of large-scale road traffic. Therefore the approach adopted to analyze the hierarchical dynamic of traffic systems is based on HMAS. To this end, several contributions have been proposed:

- [A holonofication model](#) allowing to structure the HMAS, i.e. a model allowing to build the holarchy of traffic system composed by recursive holons. A methodology enabling to create upper levels composed by super-holons from a set of sub-holons (upward approach) as well as a methodology to go back in lower levels composed by a set of sub-holons (downward approach) are proposed. The upward holonification model is based on an adaptation of the famous DBSCAN algorithm. Our adaptation

is named H-DBSCAN. The downward holonification model is based on Gaussian distribution.

- **A holonic model for the dynamic management of the holarchy.** This contribution enables the dynamic adaptation of the level of detail of the simulated holarchy. This contribution allows the proposal to deal with the compromise between simulation accuracy and availability of computational resources.
- **A multilevel indicator** is proposed to measure the consistency of the transitions between heterogeneous levels of detail. The goal is to evaluate whether the model used at the higher level correctly approximates all the behaviors of the models at the lower levels. These evaluations allow dynamically build the hierarchy of holons to simulate the behavior of the traffic system.

Furthermore, an application on highway is presented. In this application, the multilevel simulation can migrate from microscopic to mesoscopic representation by the will of designer or by the simulation needs. The results of the experiments made on several scenarios enable us to validate the hypothesis made in this research work.

The main advantages of our proposition are:

- **Several levels of detail:** In contrary to a majority of multilevel models of traffic, which focuses only on two levels of detail (e.g. micro-macro, meso-macro or meso-macro), we have proposed a multilevel model allowing a transition between micro, meso and macro level. This allows a step by step transition in order to increase the consistency of the multilevel model.
- **Dynamicity:** In contrary to most of the multilevel models of traffic, which are static i.e. representation associated to road network cannot change during runtime, we have proposed a dynamic multilevel model of traffic. In fact, our proposal allows a dynamic transition between heterogeneous levels of detail. Moreover, our proposal deals with the management of the compromise between simulation accuracy and availability of computational resources.
- **Scaling:** By managing the compromise between simulation accuracy and available computation resources, the proposal is able to scale and therefore deals with large-scale traffic.

However, this work has also drawbacks. The main drawback is related to inconsistent results when traffic is very fluid. In fact in a few presence of groups of traffic holons, their approximation into a traffic super-holon could be inconsistent because of the highly fluctuating state of the traffic. Moreover, it should be noted that the internal states of the traffic holons were generated for running the model. They should be replaced by internal states issued from field interviews.

9.2/ PERSPECTIVES

The proposal is a step towards the development of a holonic and dynamic multilevel model to deal with large-scale complex traffic scenarios exhibiting a hierarchical behavior. To go further in the development of this model, we define two axes of deepening this work. The first is related to the integration of lane change model within the proposal, and the second is related to the limitation of the execution interval of upper levels to ensure good results.

9.2.1/ INTEGRATION OF LANE CHANGE MODEL

In this thesis, only the longitudinal displacements of the vehicles, i.e. the acceleration and deceleration models, are considered. Lateral displacements of the vehicles (lane change model) are not take into account in the dynamic management of the holarchy. A lane change model is a function, which mainly takes into account the driver's desired speed, as well as the speed and the slot on the adjacent lane. If the lane change is desired and possible in consideration of the parameters, it is carried out. However, despite its great significance, lane change models have by far not been studied as extensively as the longitudinal acceleration and deceleration behavior. One reason for this is the scarcity of reliable data. For measuring lane changes, cross-sectional data from detectors are not sufficient and, therefore, only a few empirical studies about lane-changing rates as a function of traffic flow or density are available. Moreover, in the context of holonic multilevel model of traffic, the combination of several levels of detail within the same simulation increase the complexity for the integration of the lane change models. Future works will combine longitudinal and lateral displacements of the vehicles in the holarchy management.

9.2.2/ LIMITATION OF INTERVAL OF RUN-TIME OF UPPER LEVELS

Upper levels decrease the accuracy of simulation. Therefore involving them must be done carefully. To this end, involving upper levels need a limitation their run-time interval. This is to increase the consistency of the dynamic multilevel simulation of traffic. In fact, the maximum time execution of upper levels guaranteeing the consistence of the simulation need to be define. However, to do this more realistic data are needed. Future works include the limitation of interval of run-time execution of upper levels to ensures good results.

9.2.3/ DEPLOYMENT WITH REAL DATA

In this thesis the data were generated to run the model proposed. In fact, the initial features variables of the vehicles were generated and applied to run the model. Future works will include the execution of the proposal with real data obtained from field interviews or questionnaires. To this end, a survey can be envisaged on the city or country of application. It could be envisaged to make the survey in Ngaoundere city located in Cameroon (a country in Central Africa) or in other city.

IV

BIBLIOGRAPHY

BIBLIOGRAPHY

- [1] Abdoos, M., Esmaeili, A., and Ana, L.C., B. (2013). Holonic multi-agent system for traffic signals control. *Engineering Applications of Artificial Intelligence*.
- [2] Abdoos, M., Esmaeili, A., and Mozayani, N. (2012). Holonification of a network of agents based on graph theory. In Jezic, G., Kusek, M., Nguyen, N.-T., Howlett, R. J., and Jain, L. C., editors, *Agent and Multi-Agent Systems. Technologies and Applications*, pages 379–388, Berlin, Heidelberg. Springer Berlin Heidelberg.
- [3] Abouaïssa, H., Kubera, Y., and Morvan, G. (2014). Dynamic hybrid traffic flow modeling. *arXiv*.
- [4] Aristotle (2012). *The Metaphysics*. CreateSpace Independent Publishing Platform.
- [5] Aw, A. and Rascle, M. (2000). Resurrection of” second order” models of traffic flow. *SIAM journal on applied mathematics*, 60(3):916–938.
- [6] Bando, M., Hasebe, K., Nakayama, A., Shibata, A., and Sugiyama, Y. (1995). Dynamical model of traffic congestion and numerical simulation. *Physical review E*, 51(2):1035.
- [7] Baras, J. S. and Tan, X. (2004). Control of autonomous swarms using gibbs sampling. In *2004 43rd IEEE Conference on Decision and Control (CDC)(IEEE Cat. No. 04CH37601)*, volume 5, pages 4752–4757. IEEE.
- [8] Benaskeur, A. and Irandoust, H. (2008). Holonic approach for control and coordination of distributed sensors. Technical report, DEFENCE RESEARCH AND DEVELOPMENT CANADA VALCARTIER (QUEBEC).
- [9] Birant, D. and Kut, A. (2007). St-dbscan: An algorithm for clustering spatial-temporal data. *Data & Knowledge Engineering*, pages 208–221.
- [10] Bouha, N., Morvan, G., Hassane, A., and Kubera, Y. (2015). A first step towards dynamic hybrid traffic modelling. In *Proc. of 29th European Conf. on modelling and simulation (ECMS)*, pages 64–70.
- [11] Bourrel, E. and Lesort, J. (2003). Mixing micro and macro representations of traffic flow: a hybrid model based on the lwr theory. In *82th Annual Meeting of the Transportation Research Board*.

- [12] Box, G. E. P. and Muller, M. E. (1958). A note on the generation of random normal deviates. *Ann. Math. Statist.*, 29(2):610–611.
- [13] Brackstone, M. and McDonald, M. (1999). Car-following: a historical review. *Transportation Research Part F: Traffic Psychology and Behaviour*, 2(4):181–196.
- [14] Brussel, H. V., Wyns, J., Valckenaers, P., Bongaerts, L., and Peeters, P. (1998). Reference architecture for holonic manufacturing systems: Prosa. *Computers in Industry*, 37(3):255 – 274.
- [15] Buisson, J., Galland, S., Gaud, N., Gonçalves, M., and Koukam, A. (2013). Real-time collision avoidance for pedestrian and bicyclist simulation: a smooth and predictive approach. *Procedia Computer Science*, 19:815–820.
- [16] Burghout, W. (2004). *Hybrid microscopic-mesoscopic traffic simulation*. PhD thesis, Royal Institute of Technology.
- [17] Burghout, W. (2005). Mesoscopic simulation models for short-term prediction. *PREDIKT project report CTR2005*, 3.
- [18] Burghout, W., Koutsopoulos, H. N., and Andreasson, I. (2005). Hybrid mesoscopic-microscopic traffic simulation. *Transportation Research Record*, 1934(1):218–225.
- [19] Camus, B. (2015). *Environnement Multi-agent pour la Multi-modélisation et Simulation des Systèmes Complexes*. PhD thesis, Université de Lorraine.
- [20] Cao, F., Ester, M., Qian, W., and Zhou, A. (2006). Density-based clustering over an evolving data stream with noise. In *SDM*.
- [21] Cellier, F. E. and Greifeneder, J. (1991). *Continuous System Modeling*. Springer.
- [22] Champion, A. (2003). *Mécanisme de coordination multi-agent fondé sur des jeux: application à la simulation comportementale de trafic routier en situation de carrefour*. PhD thesis, Valenciennes.
- [23] Chandler, R. E., Herman, R., and Montroll, E. W. (1958). Traffic dynamics: studies in car following. *Operations research*, 6(2):165–184.
- [24] Commission, E. (2007). Towards a new culture for urban mobility. *Green paper*.
- [25] Contet, J.-M., Gechter, F., Gruer, P., and Koukam, A. (2007). Physics inspired multi-agent model for vehicle platooning. In *International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS)*.
- [26] Cossentino, M., Gaud, N., Hilaire, V., Galland, S., and Koukam, A. (2010). Aspects: an agent-oriented software process for engineering complex systems. *Autonomous Agents and Multi-Agent Systems*, 20(2):260–304.

- [27] Council, N. R. et al. (2000). *Making IT better: Expanding information technology research to meet society's needs*. National Academies Press.
- [28] David, D. and Courdier, R. (2008). Emergence as metaknowledge: refining simulation models through emergence reification. In *Cyrille Bertelle et Aladdin Ayeshe, editeurs, European Simulation and Modelling Conference (ESM'08)*, pages 25–27.
- [29] Davis C, S. and Robert G, B. (2019). Transportation energy data book edition 37.1. Technical report, Oak Ridge National Laboratory.
- [30] De Rosnay, J. (2014). *Le microscope. Vers une vision globale*. Le seuil.
- [31] Demange, J. (2012). *Un modèle d'environnement pour la simulation multiniveau- Application à la simulation de foules*. PhD thesis, Université de Technologie de Belfort-Montbéliard.
- [32] Doniec, A. (2006). *Anticipatory behaviours in multi-agent coordination: application in traffic simulation*. Theses, Université de Valenciennes.
- [33] Drogoul, A. (1993). *De la simulation multi-agents a la resolution collective de problemes: une etude de l'emergence de structures d'organisation dans les systemes multi-agents*. PhD thesis, Paris 6.
- [34] Drogoul, A., Amouroux, E., Caillou, P., Gaudou, B., Grignard, A., Marilleau, N., Tailandier, P., Vavasseur, M., Vo, D.-A., and Zucker, J.-D. (2013). Gama: A spatially explicit, multi-level, agent-based modeling and simulation platform. In *International Conference on Practical Applications of Agents and Multi-Agent Systems*, pages 271–274. Springer.
- [35] Edie, L. C. (1961). Car-following and steady-state theory for noncongested traffic. *Operations research*, 9(1):66–76.
- [36] Esmaeili, A., Mozayani, N., Motlagh, M., and Matson, E. (2017). A socially-based distributed self-organizing algorithm for holonic multi-agent systems: Case study in a task environment. *Cognitive Systems Research*, pages 21–44.
- [37] Esmaeili, A., Mozayani, N., and Motlagh, M. R. J. (2014). Multi-level holonification of multi-agent networks. In *2014 Iranian Conference on Intelligent Systems (ICIS)*, pages 1–5.
- [38] Espie, S., Gattuso, D., and Galante, F. (2006). Hybrid traffic model coupling macro- and behavioral microsimulation. Technical report.
- [39] Ester, M., Kriegel, H.-P., Sander, J., and Xu, X. (1996). A density-based algorithm for discovering clusters in large spatial databases with noise. In *2nd International Conference on Knowledge Discovery and Data mining*, pages 226–231.

- [40] Ferber, J. (1997). *Les systèmes multi-agents: vers une intelligence collective*. InterEditions.
- [41] Ferber, J. (1999). *Multi-Agent Systems. An Introduction to Distributed Artificial Intelligence*. Addison Wesley.
- [42] Ferber, J., Gutknecht, O., and F., M. (2003). Agent/group/roles: Simulating with organizations. In *ABS'03: Agent Based Simulation*.
- [43] Filip, F.-G. and Leiviskä, K. (2009). Large-scale complex systems. In *Springer Handbook of Automation*, pages 619–638. Springer.
- [44] Fischer, K., Schillo, M., and Siekmann, J. (2003). Holonic multiagent systems: A foundation for the organisation of multiagent systems. In *International Conference on Industrial Applications of Holonic and Multi-Agent Systems*, pages 71–80. Springer.
- [45] Galland, S., Balbo, F., Gaud, N., Rodriguez, S., Picard, G., and Boissier, O. (2015). A multidimensional environment implementation for enhancing agent interaction. In Bordini, R. and Elkind, E., editors, *14th Int. Conf. on Autonomous Agents and Multi-agent Systems (AAMAS15)*, pages 1801–1802, Istanbul, Turkey. IFAAMAS, ACM In-Cooperation.
- [46] Galland, S., Knapen, L., Gaud, N., Janssens, D., Lamotte, O., Koukam, A., Wets, G., et al. (2014). Multi-agent simulation of individual mobility behavior in carpooling. *Transportation Research Part C: Emerging Technologies*, 45:83–98.
- [47] Galland, S., Mualla, Y., Tchappi Haman, Igor and Zhao, H., Rodriguez, S., Najjar, A., and Gaud, N. (2020). Model transformations from the SARL agent-oriented programming language to an object-oriented programming language. *International Journal on Agent-Oriented Software Engineering*, pages 1–38.
- [48] Garbolino, E., Chéry, J.-P., and Guarnieri, F. (2019). The systemic approach: Concepts, method and tools. In *Safety Dynamics*, pages 1–30. Springer.
- [49] Garner, G. and McGlynn, P. (2018). *Intelligence Analysis Fundamentals*. CRC Press.
- [50] Gaud, N. (2007). *Holonic Multi-Agent Systems: From the analysis to the implementation. Metamodel, Methodology and Multilevel simulation*. PhD thesis, Université de Technologie de Belfort-Montbéliard, Belfort, France. In French.
- [51] Gaud, N., Galland, S., Gechter, F., Hilaire, V., and Koukam, A. (2008). Holonic multi-level simulation of complex systems: Application to real-time pedestrians simulation in virtual urban environment. *Simulation Modelling Practice and Theory, Elsevier*, pages 1659–1676.

- [52] Gazis, D. C., Herman, R., and Rothery, R. W. (1961). Nonlinear follow-the-leader models of traffic flow. *Operations research*, 9(4):545–567.
- [53] Gerber, C., Siekmann, J., and Vierke, G. (1999). Holonic multi-agent systems. *Research Center for Artificial Intelligence (DFKI) Tech. Rep. 681, German*.
- [54] Ghosh, S. (1986). On the concept of dynamic multi-level simulation. In *Proceedings of the 19th annual symposium on Simulation*, pages 201–205. IEEE Computer Society Press.
- [55] Gil-Quijano, J., Hutzler, G., and Louail, T. (2010). Accroche-toi au niveau, j'enlève l'échelle: Éléments d'analyse des aspects multiniveaux dans la simulation à base d'agents. *Revue d'intelligence artificielle*, 24(5):625–648.
- [56] Gilbert, N., Conte, R., et al. (2006). *Artificial societies: The computer simulation of social life*. Routledge.
- [57] Gipps, P. G. (1981). A behavioural car-following model for computer simulation. *Transportation Research Part B: Methodological*, 15(2):105–111.
- [58] Giret, A. and Botti, V. (2004). Holons and agents. *Journal of intelligent manufacturing*, 15(5):645–659.
- [59] Golden, B. and Perny, P. (2010). Infinite order lorenz dominance for fair multi-agent optimization. In *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems: volume 1-Volume 1*, pages 383–390.
- [60] Hans-Jürgen, B., Klaus, F., and Gero, V. (2000). Holonic transport scheduling with teletruck. *Applied Artificial Intelligence: An. International Journal*.
- [61] Helbing, D. (1998). Traffic data and their implications for consistent traffic flow modeling. *arXiv preprint cond-mat/9806221*.
- [62] Helbing, D. and Greiner, A. (1997). Modeling and simulation of multilane traffic flow. *Physical Review E*, 55(5):5498.
- [63] Hussain, I., Knapen, L., Galland, S., Bellemans, T., Janssens, D., Wets, G., et al. (2016). Organizational-based model and agent-based simulation for long-term car-pooling. *Future Generation Computer Systems*, 64:125–139.
- [64] Jaume, B. (2010). *Fundamentals of Traffic Simulation*. Springer.
- [65] Jean-Michel, C., Franck, G., Pablo, G., and Abder, K. (2007). Physics inspired multi-agent system for vehicle platooning. In *Proceedings of the 6th International Joint Conference on Autonomous Agents and Multiagent Systems, AAMAS '07*, pages 184:1–184:3, New York, NY, USA. ACM.

- [66] Jennings, N. (2001). An agent-based approach for building complex software systems. *Communications of the ACM*, 44(4):35–41.
- [67] Jennings, N. R. and Wooldridge, M. J. (1998). Applications of intelligent agents. *Agent Technology : Foundations, Applications and Markets*.
- [68] Kesting, A. and Treiber, M. (2008). How reaction time, update time, and adaptation time influence the stability of traffic flow. *Computer-Aided Civil and Infrastructure Engineering*, 23(2):125–137.
- [69] Kesting, A., Treiber, M., and Helbing, D. (2008). Agents for Traffic Simulation. Technical Report arXiv:0805.0300.
- [70] Koestler, A. (1967). *The Ghost in The Machine*. Hutchinson.
- [71] Kometani, E. and Sasaki, T. (1959). A safety index for traffic with linear spacing. *Operations research*, 7(6):704–720.
- [72] Kouvelis, P. and Yu, G. (2013). *Robust discrete optimization and its applications*, volume 14. Springer Science & Business Media.
- [73] KSONTINI, F. (2013). *Affordance based agent model : application to the traffic simulation*. Theses, Université de Valenciennes et du Hainaut-Cambresis.
- [74] Lavendelis, E. and Grundspenkis, J. (2008). Open holonic multi-agent architecture for intelligent tutoring system development. In *Proceedings of IADIS International Conference „Intelligent Systems and Agents*, pages 100–108.
- [75] Law, A. M., Kelton, W. D., and Kelton, W. D. (2000). *Simulation modeling and analysis*, volume 3. McGraw-Hill New York.
- [76] Leonard, D., Gower, P., and Taylor, N. (1989). Contram: structure of the model. Technical report.
- [77] Li, Y. and Sun, D. (2012). Microscopic car-following model for the traffic flow: the state of the art. *Journal of Control Theory and Applications*, 10(2):133–143.
- [78] Lieberman, E. and Rathi, A., K. (2005). Traffic simulation. *U.S. Dept. of Transportation*.
- [79] Liggett, T. M. (2012). *Interacting particle systems*, volume 276. Springer Science & Business Media.
- [80] Lighthill, M. J., S., F. R., and Whitham, G. B. (1955). On kinematic waves ii. a theory of traffic flow on long crowded roads. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 229(1178):317–345.

- [81] Liu, L., Huang, H., Guo, Y., and Chen, F. (2009). rdenstream, a clustering algorithm over an evolving data stream. In *2009 International Conference on Information Engineering and Computer Science*, pages 1–4.
- [82] Magne, L., Rabut, S., and Gabard, J.-F. (2000). Towards an hybrid macro-micro traffic flow simulation model. In *INFORMS spring 2000 meeting*.
- [83] Mahmoud, M. S. (1977). Multilevel systems control and applications: A survey. *IEEE transactions on Systems, Man, and Cybernetics*, 7(3):125–143.
- [84] Mammar, S., Mammar, S., and Lebacque, J. (2006). Highway traffic hybrid macro-micro simulation model. In *11th IFAC Symposium on Control in Transportation System*.
- [85] Mansalis, S., Ntoutsis, E., Pelekis, N., and Theodoridis, Y. (2018). An evaluation of data stream clustering algorithms. *Statistical Analysis and Data Mining: The ASA Data Science Journal*, 11(4):167–187.
- [86] Marcellino, F. J. and Sichman, J. S. (2010). A holonic multi-agent model for oil industry supply chain management. In *Ibero-American Conference on Artificial Intelligence*, pages 244–253. Springer.
- [87] Marcenac, P., Courdier, R., and Calderoni, S. (1998a). Towards a toolkit to study emergence in complex systems simulations.
- [88] Marcenac, P., Courdier, R., Caldéroni, S., and Soulié, J. C. (1998b). Towards an emergence machine for complex systems simulations. In *International Conference on Industrial, Engineering and Other Applications of Applied Intelligent Systems*, pages 785–794. Springer.
- [89] Martínás, K. (2004). Neumannian economy in multi-agent approach. investigation of stability and instability in economic growth. *Interdisciplinary Description of Complex Systems: INDECS*, 2(1):70–78.
- [90] Maudet, A., Touya, G., Duchêne, C., and Picault, S. (2015). Patterns multi-niveaux pour les sma. *23e Journées Francophones sur les Systèmes Multi-Agents (JF-SMA'2015)*, pages 19–28.
- [91] Michel, F. (2007). The irm4s model: the influence/reaction principle for multiagent based simulation. In *Proceedings of the 6th international joint conference on Autonomous agents and multiagent systems*, page 133. ACM.
- [92] Mohan, R. and Ramadurai, G. (2013). State-of-the art of macroscopic traffic flow modelling. *International Journal of Advances in Engineering Sciences and Applied Mathematics*, 5(2-3):158–176.

- [93] Moise, G. (2008). An agent-holon oriented methodology to build complex software systems. *Int. J. of Computers*.
- [94] Morin, E. (1981). *La Méthode. Tome1, la Nature de la nature*. Le Seuil.
- [95] Morin, E. (1990). Introduction à la pensée complexe, 158 p. *Paris: Editions du Seuil*.
- [96] Morvan, G. (2012). Multi-level agent-based modeling-a literature survey. *arXiv preprint arXiv:1205.0561*.
- [97] Morvan, G. and Jolly, D. (2012). Multi-level agent-based modeling with the influence reaction principle. *arXiv preprint arXiv:1204.0634*.
- [98] Morvan, G., Veremme, A., and Dupont, D. (2010). Irm4mls: the influence reaction model for multi-level simulation. In *International Workshop on Multi-Agent Systems and Agent-Based Simulation*, pages 16–27. Springer.
- [99] Moutari, S. and Rascle, M. (2007). A hybrid lagrangian model based on the aw-rascle traffic flow model. *SIAM Journal on Applied Mathematics*, 68(2):413–436.
- [100] Mualla, Y., Najjar, A., Galland, S., Nicolle, C., Haman Tchappi, I., Yasar, A.-U.-H., and Främling, K. (2019). Between the megalopolis and the deep blue sky: Challenges of transport with uavs in future smart cities. In *Proceedings of the 18th International Conference on Autonomous Agents and MultiAgent Systems*, pages 1649–1653. International Foundation for Autonomous Agents and Multiagent Systems.
- [101] Müller, J.-P. (2008). Towards a formal semantics of event-based multi-agent simulations. In *International Workshop on Multi-Agent Systems and Agent-Based Simulation*, pages 110–126. Springer.
- [102] Müller, J. P., Diallo, A., François, J.-C., Mathian, H., Sanders, L., Phan, D., and Waldeck, R. (2011). Building ontologies from a variety of points of view.
- [103] Muzy, A., Aiello, A., Santoni, P.-A., Zeigler, B. P., Nutaro, J. J., and Jammalamadaka, R. (2005). Discrete event simulation of large-scale spatial continuous systems. In *2005 IEEE International Conference on Systems, Man and Cybernetics*, volume 4, pages 2991–2998. IEEE.
- [104] Na, H. S. and Banerjee, A. (2014). An agent-based discrete event simulation approach for modeling large-scale disaster evacuation network. In *Proceedings of the Winter Simulation Conference 2014*, pages 1516–1526. IEEE.
- [105] Navarro, L., Corruble, V., Flacher, F., and Zucker, J.-D. (2012). Mesoscopic level: A new representation level for large scale agent-based simulations. In *Proceedings of the 4th International Conference on Advances in System Simulation*. Citeseer.

- [106] Navarro, L., Flacher, F., and Corruble, V. (2011). Dynamic level of detail for large scale agent-based urban simulations. In *The 10th International Conference on Autonomous Agents and Multiagent Systems-Volume 2*, pages 701–708. International Foundation for Autonomous Agents and Multiagent Systems.
- [107] Newell, G. (1989). Comments on traffic dynamics. *Transportation Research Part B: Methodological*, 23(5):386 – 389.
- [108] Ngueutsa, R. (2012). *Croyances et comportements de sécurité des usagers et agents du trafic routier: une étude des perceptions et de l'explication naïve des accidents de la route au Cameroun*. PhD thesis, Université de Grenoble.
- [109] O'Leary, D. E. (1998). Developing multiple-agent systems is more than top-down vs. bottom-up. *IEEE Intelligent Systems and their Applications*, 13(2):2–5.
- [110] Ören, T. (2011a). A critical review of definitions and about 400 types of modeling and simulation. *SCS M&S Magazine*, 2(3):142–151.
- [111] Ören, T. (2011b). The many facets of simulation through a collection of about 100 definitions. *SCS M&S Magazine*, 2(2):82–92.
- [112] Organisation Mondiale de la Santé (2009). Rapport de la situation sur la sécurité routière dans le monde : il est temps d'agir. Technical report.
- [113] Park, K. and Willinger, W. (2005). *The Internet as a large-scale complex system*, volume 3. Oxford University Press, USA.
- [114] Perny, P. and Weng, P. (2010). On finding compromise solutions in multiobjective markov decision processes. In *ECAI*, volume 215, pages 969–970.
- [115] Picault, S. and Mathieu, P. (2011). An interaction-oriented model for multi-scale simulation. In *Twenty-Second International Joint Conference on Artificial Intelligence*.
- [116] Pipes, L. A. (1953). An operational analysis of traffic dynamics. *Journal of applied physics*, 24(3):274–281.
- [117] Poschinger, A., Kates, R., and Keller, H. (2002). Coupling of concurrent macroscopic and microscopic traffic flow models using hybrid stochastic and deterministic disaggregation. *Transportation and Traffic Theory for the 21st century*.
- [118] Richards, P. I. (1956). Shock waves on the highway. *Operations research*, 4(1):42–51.
- [119] Rodriguez, S. (2005). *From analysis to design of Holonic Multi-Agent Systems: A Framework, Methodological Guidelines and Applications*. PhD thesis, Université de Technologie de Belfort-Montbéliard.

- [120] Rodriguez, S., Gaud, N., and Galland, S. (2014). SARL: a general-purpose agent-oriented programming language. In *the 2014 IEEE/WIC/ACM International Conference on Intelligent Agent Technology*, Warsaw, Poland. IEEE Computer Society Press.
- [121] Rodriguez, S., Hilaire, V., and Koukam, A. (2003). Towards a methodological framework for holonic multi-agent systems. In *Fourth International Workshop of Engineering Societies in the Agents World*, pages 179–185, Imperial College London, UK (EU).
- [122] Rodriguez, S., Hilaire, V., and Koukam, A. (2007). Towards a holonic multiple aspect analysis and modeling approach for complex systems: Application to the simulation of industrial plants. *Simulation Modelling Practice and Theory*, 15(5):521–543.
- [123] Rothengatter, T. (1997). Psychological aspects of road user behaviour. *APPLIED PSYCHOLOGY: AN INTERNATIONAL REVIEW: SPECIAL ISSUE-TRAFFIC PSYCHOLOGY*, 46(3).
- [124] Roulet-Dubonnet, O., Lind, M., Gellein, L. T., Nyen, P. ., Lien, T., and Skavhaug, A. (2009). Development of a holonic free-roaming agv system for part manufacturing. In Mařík, V., Strasser, T., and Zoitl, A., editors, *Holonic and Multi-Agent Systems for Manufacturing*, pages 215–224, Berlin, Heidelberg. Springer Berlin Heidelberg.
- [125] Russell, S. J. and Norvig, P. (2016). *Artificial intelligence: a modern approach*. Malaysia; Pearson Education Limited,.
- [126] said EL Hmam, M., Abouaissa, H., Jolly, D., and Benasser, A. (2006). Macro-micro simulation of traffic flow. *IFAC Proceedings Volumes*, 39(3):351 – 356. 12th IFAC Symposium on Information Control Problems in Manufacturing.
- [127] Scerri, D., Drogoul, A., Hickmott, S., and Padgham, L. (2010). An architecture for modular distributed simulation with agent-based models. In *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems: volume 1-Volume 1*, pages 541–548. International Foundation for Autonomous Agents and Multiagent Systems.
- [128] Scheutz, M., Madey, G., and Boyd, S. (2005). tmans—the multi-scale agent-based networked simulation for the study of multi-scale, multi-level biological and social phenomena. In *Proceedings of Spring Simulation Multiconference (SMC 05), Agent-Directed Simulation Symposium*.
- [129] Sewall, J., Wilkie, D., and Lin, M. C. (2011). Interactive hybrid simulation of large-scale traffic. *ACM Trans. Graph.*, 30(6):135:1–135:12.
- [130] Shafaei, S. and Aghaee, N. G. (2008). Biological network simulation using holonic multiagent systems. In *Tenth International Conference on Computer Modeling and Simulation (uksim 2008)*, pages 617–622. IEEE.

- [131] Sheard, S. A. and Mostashari, A. (2009). Principles of complex systems for systems engineering. *Systems Engineering*, 12(4):295–311.
- [132] Siebert, J. (2011). *Approche multi-agent pour la multi-modélisation et le couplage de simulations: application à l'étude des influences entre le fonctionnement des réseaux ambiants et le comportement de leurs utilisateurs*. PhD thesis, Université Henri Poincaré-Nancy 1.
- [133] Šiljak, D. D. (1978). *Large-scale dynamic systems: stability and structure*, volume 2. North Holland.
- [134] Simon, H. A. (1991). The architecture of complexity. In *Facets of systems science*, pages 457–476. Springer.
- [135] Smuts, J. C. (1926). *Holism and evolution*.
- [136] Solanki, R. S., Gorti, J. K., and Southworth, F. (1998). Using decomposition in large-scale highway network design with a quasi-optimization heuristic. *Transportation Research Part B: Methodological*, 32(2):127–140.
- [137] Solovyev, A., Mikheev, M., Zhou, L., Dutta-Moscato, J., Ziraldo, C., An, G., Vodovotz, Y., and Mi, Q. (2010). Spark: a framework for multi-scale agent-based biomedical modeling. In *Proceedings of the 2010 Spring Simulation Multiconference*, page 3. Society for Computer Simulation International.
- [138] Sommerville, I., Cliff, D., Calinescu, R., Keen, J., Kelly, T., Kwiatkowska, M., Mcdermid, J., and Paige, R. (2011). Large-scale complex it systems. *arXiv preprint arXiv:1109.3444*.
- [139] Soyez, J.-B., Morvan, G., Dupont, D., and Merzouki, R. (2012). A methodology to engineer and validate dynamic multi-level multi-agent based simulations. In *International Workshop on Multi-Agent Systems and Agent-Based Simulation*, pages 130–142. Springer.
- [140] Soyez, J.-B., Morvan, G., Merzouki, R., and Dupont, D. (2014). A multilevel agent-based approach to model and simulate systems of systems. In *InTraDE project final workshop*.
- [141] Steiniger, A., Krüger, F., and Uhrmacher, A. M. (2012). Modeling agents and their environment in multi-level-devs. In *Proceedings of the Winter Simulation Conference*, page 233. Winter Simulation Conference.
- [142] Taillandier, P., Vo, D.-A., Amouroux, E., and Drogoul, A. (2010). Gama: a simulation platform that integrates geographical information data, agent-based modeling and multi-scale control. In *International Conference on Principles and Practice of Multi-Agent Systems*, pages 242–258. Springer.

- [143] Tchappi, I., Kamla, V., Galland, S., and Kamgang, J. (2017). Towards an multilevel agent-based model for traffic simulation. pages 887–892. *Procedia Computer Science*.
- [144] Tchappi, I. H., Galland, S., Kamla, V. C., and Kamgang, J. C. (2018a). A brief review of holonic multi-agent models for traffic and transportation systems. *Procedia computer science*, 134:137–144.
- [145] Tchappi, I. H., Galland, S., Kamla, V. C., Kamgang, J.-C., Nono, C. M. S., and Zhao, H. (2018b). Holonification model for a multilevel agent-based system. *Personal and Ubiquitous Computing*.
- [146] Torday, A., Gerodimos, A., et al. (2010). Combining mesoscopic and microscopic simulation in an integrated environment as a hybrid solution. *IEEE Intelligent Transportation Systems Magazine*, 2(3):25–33.
- [147] Treiber, M., Hennecke, A., and Helbing, D. (2000). Congested traffic states in empirical observations and microscopic simulations. *Physical Review E* 62.
- [148] Treuil, J. P., A., D., and Zucker, J. D. (2008). *Modélisation et simulation à base d'agents*. Dunod.
- [149] Uhrmacher, A. M., Ewald, R., John, M., Maus, C., Jeschke, M., and Biermann, S. (2007). Combining micro and macro-modeling in devs for computational biology. In *Proceedings of the 39th conference on Winter simulation: 40 years! The best is yet to come*, pages 871–880. IEEE Press.
- [150] Ulieru, M. and Geras, A. (2002). Emergent holarchies for e-health applications: a case in glaucoma diagnosis. In *IEEE 2002 28th Annual Conference of the Industrial Electronics Society. IECON 02*, volume 4, pages 2957–2961. IEEE.
- [151] Vangheluwe, H., De Lara, J., and Mosterman, P. J. (2002). An introduction to multi-paradigm modelling and simulation. In *Proceedings of the AIS'2002 conference (AI, Simulation and Planning in High Autonomy Systems), Lisboa, Portugal*, pages 9–20.
- [152] Vèque, V., Kaisser, F., Johnen, C., and A., B. (2013). Convoy: a new cluster-based routing protocol for vehicular networks. In *Vehicular Networks: Models and Algorithms*. ISTE Publishing Knowledge /John Wiley and Sons Inc.
- [153] Wang, W.-J. and Luoh, L. (2004). Stability and stabilization of fuzzy large-scale systems. *IEEE Transactions on Fuzzy Systems*, 12(3):309–315.
- [154] World Health Organization (2016). Mortality 2016 and 2060 – baseline scenario. Accessed march 25, 2019.

- [155] Yang, Q., Koutsopoulos, H. N., and Ben-Akiva, M. E. (2000). Simulation laboratory for evaluating dynamic traffic management systems. *Transportation Research Record*, 1710(1):122–130.
- [156] Zeigler, B., Muzy, A., and Yilmaz, L. (2009). *Artificial Intelligence in Modeling and Simulation*, pages 344–368. Springer New York, New York, NY.
- [157] Zeigler, B. P., Kim, T. G., and Praehofer, H. (2000). *Theory of modeling and simulation*. Academic press.
- [158] Zeng, Y.-z. and Zhang, N. (2016). Review and new insights of the car-following model for road vehicle traffic flow. In *Proceedings of the 6th International Asia Conference on Industrial Engineering and Management Innovation*, pages 87–96. Springer.
- [159] Zhang, H. M. (2002). A non-equilibrium traffic model devoid of gas-like behavior. *Transportation Research Part B: Methodological*, 36(3):275–290.

LIST OF FIGURES

2.1	Example of emergence	13
2.2	Example of road traffic emergence	14
2.3	Two different projections of a stack of two cubes	18
2.4	Road traffic system from the perspective of the individuals (the vehicles) . .	18
2.5	Road traffic system from the perspective of the whole (the flow)	18
2.6	Road traffic, a large-scale complex system	19
2.7	Framework of M&S	23
2.8	Summary of large-scale complex systems	28
2.9	Summary of multilevel modeling and simulation	29
3.1	Levels of detail of traffic models [32]	33
3.2	Some car following model parameters	35
3.3	Coupling schema proposed by Mammar et al. [84]	43
3.4	Hybrid model principle proposed by said EL Hmam et al. [126]	44
3.5	Hybrid Langrangian Model proposed by Moutari and Rascle [99]	44
3.6	Integration architecture proposed by Burghout et al. [18]	45
3.7	Hybridization model proposed by Bourrel and Lesort [11]	46
3.8	Summary of monolevel models of traffic	51
3.9	Summary of multilevel models of traffic	52
4.1	Sierpiński triangle	61
4.2	A holarchy with three holarchical levels [50].	62
4.3	Example of the holonic structure of a university [50]	63
4.4	Intra-level and inter- level communication [119]	64
4.5	Holonic observation [44]	68

4.6	Downward holonification process	69
4.7	Bottom-up holonification process	70
4.8	Summary of HMAS	72
4.9	Summary of Holons	73
5.1	Summary of Research Methodology	83
6.1	Example of upward vehicles simulation holarchy	87
6.2	Traffic short case	90
6.3	Fine/coarse representation that is lower/upper level representation	91
6.4	Terminology of DBSCAN	92
6.5	DBSCAN drawback: database example which contains clusters with different densities	94
6.6	Organizational model	95
6.7	Example of downward vehicles simulation holarchy	99
6.8	Downward gaussian generation of sub-holons	100
6.9	Summary of holonification of traffic system	101
7.1	An Example of Level Transition of the Multilevel Simulation	105
7.2	Interaction model in no transition case	107
7.3	Interaction model in transition to coarser representation case	108
7.4	Interaction model in transition to finer representation case	109
7.5	Summary of holonic and dynamic traffic model	119
8.1	SARL Compilation Process [47]	123
8.2	Initial case study: execution scenarios on two levels of detail	125
8.3	Scenario 1 and 2: from A to B	125
8.4	Scenario 1: from B to C	126
8.5	Scenario 2: from B to C	127
8.6	Scenario 1: from C to D	127
8.7	Scenario 2: from C to D	128
8.8	Evaluation of accuracy lost by scenario 2	128

8.9 Evaluation of computational cost won by scenario 2	129
8.10 Modified case study: executions scenarios on three levels of detail	129
8.11 Evaluation of accuracy lost by scenario 3	130
8.12 Evaluation of computational cost won by scenario 3	130
8.13 H-DBSCAN performances	131
8.14 Model Performance	132

LIST OF TABLES

2.1	Examples of past troubled large-scale systems [27]	15
3.1	Advantages and drawbacks of traffic models	42
3.2	Some static multilevel models of road traffic flow [143]	47
3.3	Some dynamic multilevel models of road traffic flow [143]	49
4.1	Main differences between Agents and Holons based on [58]	65
4.2	Main differences between MAS and HMAS	65

LIST OF DEFINITIONS

1	Definition: System according to De Rosnay [30]	10
2	Definition: Complexity according to Morin [95]	11
3	Definition: Complex System according to Sheard and Mostashari [131] . . .	12
4	Definition: Complex System according to Simon [134]	12
5	Definition: Emergence according to Drogoul [33]	13
6	Definition: Large-Scale System according to Soyez et al. [140], Council et al. [27]	16
7	Definition: Large-Scale Complex System according to Šiljak [133]	17
8	Definition: Large-Scale Complex System according to Mahmoud [83]	17
9	Definition: Model according to Treuil et al. [148]	21
10	Definition: Model according to Zeigler et al. [156]	21
11	Definition: Simulation according to Treuil et al. [148], Cellier and Greifeneder [21]	22
12	Definition: Simulation according to Law et al. [75]	22
13	Definition: Simulation of Traffic according to Champion [22]	23
14	Definition: Level of detail according to Morvan [96]	24
15	Definition: Multilevel Modeling according to Morvan [96]	24
16	Definition: Multilevel Simulation according to Gaud [50]	25
17	Definition: Agent according to Russell and Norvig [125]	54
18	Definition: Agent according to Jennings and Wooldridge [67]	54
19	Definition: Multi-Agent System according to Ferber [40]	56
20	Definition: Multiagent System according to Jennings and Wooldridge [67] .	56
21	Definition: Holon according to Koestler [70]	61
22	Definition: Holonic Multi-Agent Systems according to Gerber et al. [53] . . .	61

23	Definition: Holarchy according to Gerber et al. [53]	61
24	Definition: Holonification according to Gaud [50]	62
25	Definition: Holon in HMAS according to Gerber et al. [53]	62
26	Definition: Super-holon according to Rodriguez [119]	63
27	Definition: Sub-holon according to Rodriguez [119]	63
28	Definition: Atomic holon according to Rodriguez [119]	63
29	Definition: Group of vehicles, inspired by Gaud [50]	89
30	Definition: Convoy, inspired by Vèque et al. [152]	89
31	Definition: Neighborhood	91
32	Definition: Eps-neighborhood	92
33	Definition: Core object	92
34	Definition: Directly density-reachable	92
35	Definition: Density-reachable	92
36	Definition: Density-connected	92
37	Definition: Density-based cluster	93
38	Definition: Border object	93
39	Definition: Upward Switch	105
40	Definition: Downward Switch	105

V

ANNEX

PUBLICATIONS OF THE AUTHOR

In this annex chapter, the list of the publications of IGOR TCHAPPI HAMAN are provided. The following table shows the number of publications per type:

Total numbers of publications by IGOR TCHAPPI HAMAN	
Indexed international journal with reading committee	3
International conference with reading committee	7
National conference with reading committee	3
National conference without proceeding	1

The publications are listed in two categories: (i) the publications that are directly related to the content of this thesis, and (ii) the publications that are not directly related to the content of this thesis, but to which IGOR TCHAPPI HAMAN has provided a concrete contribution.

A.1/ PUBLICATIONS THAT ARE RELATED TO THIS PHD THESIS

Numbers of publications related to this PhD thesis	
Indexed international journal with reading committee	2
International conference with reading committee	3
National conference with proceedings	1
National conference without proceeding	1

2020

- Igor TCHAPPI HAMAN, Stéphane GALLAND, Vivient corneille KAMLA, Jean-claude KAMGANG, Yazan MUALLA, Amro NAJJAR and Vincent HILAIRE. "A Critical Review of Holonic Technology in Traffic and Transportation Fields". In Journal of Engineering Applications of Artificial Intelligence (EAAI), DOI: 10.1016/j.engappai.2020.103503, Rank: Q1, Impact Factor: 3.526, 2020.

2019

- Igor TCHAPPI HAMAN, Stéphane GALLAND, Yazan MUALLA, Amro NAJJAR, Vivient Corneille KAMLA, Jean-Claude KAMGANG. "Modèle dynamique et multi-niveau holonique basé sur la densité: application au trafic routier à grande échelle." In Proc. of Journées Francophones sur les Systèmes Multiagents (JFSMA19), Toulouse, France, pp. 136-145, PFIA-19, Toulouse, France, Association Francaise d'Intelligence Artificielle, 2019.

2018

- Igor TCHAPPI HAMAN, Stéphane GALLAND, Vivient Corneille KAMLA, Jean-Claude KAMGANG, Cyrille Merleau NONO SAHA, Hui ZHAO. "Holonification Model for a Multilevel Agent-based System. Application to Road Traffic." In Journal of Personal and Ubiquitous Computing, Springer, DOI: 10.1007/s00779-018-1181-y, Rank: Q2, Impact Factor: 1.735, 2018.
- Igor TCHAPPI HAMAN, Stéphane GALLAND, Vivient Corneille KAMLA, Jean-Claude KAMGANG. "A Brief Review of Holonic Multi Agent Models for Traffic and Transportation Systems." In Proc. of The 15th International Conference on Mobile Systems and Pervasive Computing (MobiSPC 2018), Elhadi SHAKSHUKI, Ansar-UI-Haque YASAR (eds.), pp. 137-144, Canary Islands, Spain, Elsevier, vol. 134, 2018. DOI: 10.1016/j.procs.2018.07.154.
- Igor TCHAPPI HAMAN, Stéphane GALLAND, Vivient Corneille KAMLA, Jean-Claude KAMGANG. "Holonification of Road Traffic based on Graph Theory." In Proc. of 13th International Conference Cellular Automata for Research and Industry (ACRI18), the 5th Workshop on Traffic and Cellular Automata (TCA18), Lectures Notes in Computer Science, 2018.

2017

- Igor TCHAPPI HAMAN, Stéphane GALLAND, Vivient Corneille KAMLA, Jean-Claude KAMGANG. "Traffic Simulation with an Organizational and Multilevel Agent-based Model." In Proc. of FUTURMOB17 Workshop, Burgundy Franche-Comté University, Montbéliard, France, 2017.
- Igor TCHAPPI HAMAN, Vivient Corneille KAMLA, Stéphane GALLAND, Jean-Claude KAMGANG. "Towards an Multilevel Agent-based Model for Traffic Simulation." In Proc. of 6th International Workshop on Agent-based Mobility, Traf-

fic and Transportation Models, Methodologies and Applications (ABMTRANS'17), Springer, 2017.

A.2/ OTHER CONTRIBUTIONS

Numbers of other publications	
Indexed international journal with reading committee	1
International conference with reading committee	4
National conference with reading committee	2

2020

- Hui ZHAO, Yazan MUALLA, Igor TCHAPPI HAMAN, Stéphane GALLAND, Tom BELLEMANS and Ansar-ul-haque YASAR. "Decision-Making under Time Pressure when Rescheduling Daily Activities." In Proc. of the 11th International Conference on Ambient Systems, Networks and Technologies (ANT), Warsaw, Poland, 2020.
- Yazan MUALLA, Igor TCHAPPI HAMAN, Amro NAJJAR, Timotheus KAMPIK, Stéphane GALLAND and Christophe NICOLLE. "Human-Agent Explainability: An Experimental Case Study on the Filtering of Explanations". In procs of the 12th International Conference on Agents and Artificial Intelligence (ICAART 2020), Valletta, Malta, 2020.
- Stéphane GALLAND, Yazan MUALLA, Igor TCHAPPI HAMAN, Hui ZHAO, Sebastian RODRIGUEZ, Amro NAJJAR and Nicolas GAUD. "Model Transformations from the SARL Agent-Oriented Programming Language to an Object-Oriented Programming Language". In International Journal on Agent-Oriented Software Engineering, pp. 1-38, 2020.

2019

- Yazan MUALLA, Amro NAJJAR, Olivier BOISSIER, Stéphane GALLAND, Igor TCHAPPI HAMAN, Robin VANET. "A Cyber-Physical System for Semi-autonomous Oil&Gas Drilling Operations." In Proc. of 5th Workshop on Collaboration of Humans, Agents, Robots, Machines and Sensors (CHARMS 2019), Naples, Italy, IEEE Computer Society Press, 2019. DOI: 10.1109/IRC.2019.00107.
- Yazan MUALLA, Amro NAJJAR, Stéphane GALLAND, Christophe NICOLLE, Igor TCHAPPI HAMAN, Ansar-UI-Haque YASAR, Kary FRÄMLING. "Between the Megalopolis and the Deep Blue Sky: Challenges of Transport with UAVs in Future

Smart Cities.” In Proc. of the International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2019), Montreal, Canada, pp. 1649-1653, 2019. ISBN 978-1-4503-6309-9.

- Yazan MUALLA, Igor TCHAPPI HAMAN, Amro NAJJAR, Stéphane GALLAND, Robin VANET, Olivier BOISSIER. "Modélisation multi-agent des opérations semi-autonomes dans un système cyber-physique de forage pétrolier ou gazier." In Proc. of Journées Francophones sur les Systèmes Multiagents (JFSMA19), pp. 126-135, PFIA-19, Toulouse, France, Association Française d'Intelligence Artificielle, 2019.
- Emmanuel Dimitry NGOUNOU NTOUKAM, Vivient Corneille KAMLA, Yazan MUALLA, Igor TCHAPPI HAMAN, Stéphane GALLAND, Jean-Claude KAMGANG, Yves Sébastien EMVUDU WONON. "Towards a multi-agent model to prevent damage caused by cocoa mirids to cocoa pods." In Proc. of Les 17e Rencontres des Jeunes Chercheurs en Intelligence Artificielle (RJCIA), Toulouse, France, pp. 10-17, Toulouse, France, 2019.

Title: Dynamic Multilevel and Holonic Model for the Simulation of a Large-Scale Complex System with Spatial Environment - Application to Road Traffic

Keywords: Holonic Multiagent System, Multilevel Modeling and Simulation, Dynamic, Scalability, Road Traffic

Abstract:

Nowadays, with the emergence of connected objects and cars, road traffic systems become more and more complex and exhibit hierarchical behaviours at several levels of detail. The multilevel modeling approach is an appropriate approach to represent traffic from several perspectives. Multilevel models are also an appropriate approach to model large-scale complex systems such as road traffic. However, most of the multilevel models of traffic proposed in the literature are static because they use a set of predefined levels of detail and these representations cannot change during simulation. Moreover, these multilevel models generally consider only two levels of detail.

Few works have been interested on the dynamic multilevel traffic modeling. This thesis proposes a holonic multilevel and dynamic traffic model for large scale traffic systems. The dynamic migration of the levels of detail during the execution of the simulation allows to adapt the model to the constraints related to the quality of the results or to the available computing resources. The proposal extends the DBSCAN algorithm in the context of holonic multi-agent systems. In addition, a methodology allowing a dynamic transition between the different levels of detail is proposed. Multilevel indicators based on standard deviation are also proposed in order to assess the consistency of the simulation results.

Titre : Modèle dynamique multiniveau et holonique pour la simulation d'un système complexe à grande échelle avec environnement spatial - Application à la simulation de trafic routier

Mots-clés : Système Multi-Agent Holonique; Modélisation et Simulation Multiniveaux, Dynamique, Passage à l'Echelle, Trafic routier

Résumé :

De nos jours, avec l'émergence d'objets et de voitures connectés, les systèmes de trafic routier deviennent de plus en plus complexes et présentent des comportements hiérarchiques à plusieurs niveaux de détail. L'approche de modélisation multiniveaux est une approche appropriée pour représenter le trafic sous plusieurs perspectives. Les modèles multiniveaux constituent également une approche appropriée pour modéliser des systèmes complexes à grande échelle comme le trafic routier. Cependant, la plupart des modèles multiniveaux de trafic proposés dans la littérature sont statiques car ils utilisent un ensemble de niveaux de détail prédéfinis et ces représentations ne peuvent pas commuter pendant la simulation. De plus ces modèles multiniveaux considèrent

généralement seulement deux niveaux de détail. Très peu de travaux se sont intéressés à la modélisation dynamique multiniveau de trafic. Cette thèse propose un modèle holonique multiniveau et dynamique du trafic à grande échelle. La commutation dynamique des niveaux de détail lors de l'exécution de la simulation permet d'adapter le modèle aux contraintes liées à la qualité des résultats ou aux ressources de calcul disponibles. La proposition étend l'algorithme DBSCAN dans le contexte des systèmes multi-agents holoniques. De plus, une méthodologie permettant la commutation dynamique entre les différents niveaux de détail est proposée. Des indicateurs multiniveaux basés sur l'écart type sont aussi proposés afin d'évaluer la cohérence des résultats de la simulation.