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Agent-Based Simulation of urban goods distribution: a literature review

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Abstract

Agent-based simulation (ABS) appears to be a suitable tool for research and application in the field of city logistics. In this paper, an attempt was made to classify the current literature on ABS in urban freight distribution following some homogeneity criteria. A set of six criteria was adopted and relevant papers were classified accordingly. It emerges that agent-based simulation models are suitable for use in simulating urban freight distribution, identifying a set of agents (at most, one agent per stakeholder) that operate to achieve their objectives, following rules, interacting, and learning from experience. However, this approach is still to be fully developed: the applications provided in the literature are only for test cases, refer to small study areas and a limited number of agents.

Keywords: agent based simulation; city logistics; literature review.

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1. Introduction

Goods distribution in urban areas is fundamental for city life and for satisfying citizens' needs but, at the same time, produces significant economic, social and environmental impacts on transport cost sustainability. In recent years, urban economies have been evolving rapidly towards a higher degree of material intensity: store inventory levels have shrunk and businesses are increasing their restocking activities based on the just-in-time concept (Browne et al., 2012). Following such changes, the demand for transport carriers and couriers is characterized by more frequent and customized deliveries, whilst the relevant negative externalities are ever-increasing. Thus, the challenge facing urban planners is to find solutions that can reduce impacts without penalizing the life of the city, through sustainable city logistics solutions/measures.

Such city logistics measures can be classified into strategic, tactical and operative, and those mainly implemented concern freight demand management (e.g. access time windows, vehicle access constraints and area pricing), delivery area management and two-level distribution systems (e.g. transit points and urban consolidation centers). The measures can have effects that in turn can be classified as internal or external and of first or second order (Nuzzolo and Comi, 2014 a&b).

In order to define and assess suitable city logistics measures, models of the goods distribution system are implemented and applied. In general, the main actors of the distribution system are:

- the shippers: goods producers, wholesalers, distributors, freight forwarders;
- the transport providers: carriers, couriers, own account;
- the receivers: large and small retailers and end-consumers.

The main choice dimensions in general for shippers include transport service providers (own account or third party), while for transport providers the choice dimensions concern vehicle type, delivery time and route.

It is assumed that each actor makes choices to maximize an objective function and that, after a certain time, a steady-state is reached, where choices other than the last are unable to improve the objective value. In general the aim of the model is to reproduce the final steady-state of the overall system, rather than reproduce the process that generates this state.

The inputs of the model system are the time-dependent Origin-Destination matrices of deliveries from the last distribution node to the final destination. The required outputs in general are the internal transport costs and the vehicle flows on the network. In turn, these outputs can become the inputs of external cost models. For example, flows may become inputs of pollutant emission models.

A goods distribution model system includes some mathematical models: demand models that reproduce the actor's choices given a transport network state (Nuzzolo and Comi, 2014a; Polimeni and Vitetta, 2014); supply models that allow to network states to be reproduced; and demand-supply interaction models, which allow a steady-state configuration of the distribution system to be obtained. Demand-supply interaction approaches can use analytical models or computer simulation models. In analytical demand-supply interaction models, the problem of determining the steady-state is solved for example through solution of fixed-point problems, applying suitable algorithms. Computer simulation models, applying algorithms and equations within computer programs that seek to capture the behaviour of actors, are more suitable to take in to account the complex rule governing the goods distribution system. Further, such models also account for the complex interaction among the different actors, as they seek to obtain the system states reproducing the choices of each actor and the reactions to such choices. Agent-Based Simulation (ABS) models represent a particular class of computer simulation models. Agent-based models are microscale models that simulate the simultaneous operations and interactions of multiple agents that act in a well-defined environment. Individual agents are typically assumed as (bounded) rational, acting to maximize their performance measure (e.g. to obtain economic benefit), using heuristics or simple decision-making rules (Russel and Norvig, 2010). However, the knowledge of the current state of the environment is not always enough to decide what to do: sometimes the agent needs a goal information describing the desirable situations. ABS agents may experience "learning", adaptation, allowing the simulated states to converge to a steady-state configuration, if any. In ABS, an agent chooses actions to maximize its utility, according to the external performance measure. As noted by Bankes (2002), ABS allows the relaxation of several unrealistic assumptions often employed in other approaches (i.e. linearity, homogeneity, stationarity).

From a general point of view, the problem of optimizing freight transportation can be decomposed (Di Febbraro et al., 2016) into a set of sub-problems (each representing the operations of an actor involved in logistic chain). Even if the ABS is also useful to simulate transport between large regions, as proposed in Holmgren et al. (2012 and 2013), and to simulate freight distribution when external factors (e.g. accidents, flooding) affect the system (de Oliveira et al., 2016), below only applications for city logistics are considered.

Boussier et al. (2009) and Tamagawa et al. (2010) were among the first proposers of applying agent-based simulation in the field of city logistics. The actors in urban freight (i.e. distribution wholesalers, administrators, shippers, carriers, intermediaries, retailers, end-consumers) have conflicting interests, different information, and operate with an individual plan. ABS allows the interactions among the above actors to be represented.

The contribution of this paper is to provide a categorized literature review on ABS, focused on urban goods distribution, following some homogeneity criteria. Others have sought to provide a review, such as Davidson et al. (2005), who focus on long-distance freight transport, while in Maggi and Vallino (2016) the interest is at the urban level (both for freight distribution and passenger transport). In both papers, a set of classification criteria is formalized to develop the review. Davidson considers the problem description (domain, mode, time horizon), the approach (usage, agent control and attitude, model structure), and the results (maturity of the model and comparison with other approaches). Maggi and Vallino, also recalling some criteria used by Davidson, consider model intentions, the type of agents, geographical dimensions, the type of data, the time horizon, the structure, the agent attitude, and the maturity of the model. Both papers show that ABS is an approach that can contribute significantly to advancing the literature although extensive field experiments are required before the approach can be considered mature.

In this paper, with respect to other literature reviews, we seek to define the intention of the model by distinguishing the application domain and the simulated impacts. Moreover, attention is focused on agent objectives and behavior.

The rest of the paper is structured as follows. Section 2 reports a brief analysis of the classification criteria adopted. In Section 3 a selected list of papers from the literature is examined. Finally, in Section 4, some conclusions are drawn. An appendix is provided, including a table with the classified papers.

2. Classification criteria

To provide a classification for the literature review, a set of criteria is needed to identify the main features of a specific paper. In this section, a brief explanation of the classification criteria adopted is reported. The following criteria (partially gathered from the literature) are considered:

1) *Application domain*: the application domain. Some papers use ABS to simulate the effects of city logistics measures; others to solve vehicle routing problems and so on.
2) *Simulated impacts*: the type of impacts that may be assessed with the proposed model. In this case, ABS is often coupled with another model to measure the impacts deriving from the simulated scenario (e.g. external transport costs).
3) *Type of actors*: the type and characteristics of the actors considered in the simulation may be taken into account. The stakeholders may not be the only ones directly involved in the freight distribution process (as carriers, shippers, …) and other actors may be considered (namely, end-consumers, residents, city planners, …)
4) *Agent objective and behavior*: this criterion identifies some interaction characteristics between agents. Such characteristics may take the form of: interaction (whether and in what way agents interact with other actors); cooperation (whether agents cooperate to achieve results even if cooperation can limit the achievement of personal goals); competition (whether the agent is selfish and fails to consider the other agents fulfilling his/her objective). Moreover, the type of objective of each agent is considered (i.e. cost minimization, profit maximization, emissions minimization, ….)
5) *Type of application*: this criterion is intended to be a measure of the maturity level of the proposed model, identifying whether the model was applied in a real case or only in a test application or for proof of concept.

Table 1 summarizes the criteria adopted, with a short description of each criterion and an example of elements considered.

Table 1. Adopted criteria

Criteria	Description	Example
Application domain	field where the simulation is applied	• Tactical-operative city logistics measures assessment • UDC effect oriented • Access management • Vehicle routing problems
Simulation impacts	impacts from the simulated scenario	• Environmental • Economic • Social
Type of actors	actors in the simulation	• Carriers • Shippers • …
Agent objective and behavior	objective function and agent attitude	• Cooperation/Competition • Interaction • cost minimization, • profit maximization, • emissions minimization …
Type of application	application proposed to test the formulation	• Prof of concept • Test case • Real application • …

Naturally, other classification criteria could be adopted. Meersman et al. (2016) indicate a series of challenges facing freight transport in the near future. These challenges, depicted for international freight transport, could be transferred (with appropriate modifications) in urban goods distribution. For example, ABS can be useful to evaluate as the main transport data reflects or reveals the actual choices made by the decision-makers involved in the process. However, an analysis of current literature on ABS applied to urban goods distribution, suggests considering at least the criteria reported in Table 1 (without prejudice to the fact that the proposed classification does not and cannot be exhaustive).

3. Literature review

A selected set of papers from the literature were considered. The criteria, as defined in section 2, were applied to each paper, the results being summarized in Table A.1, where each column represents a criterion and each row a paper. In order to analyze the different strands developed in ABS applied to urban freight distribution, the classification provided is application-oriented and therefore the type of application domain is the main feature adopted. Moreover, we grouped the literature review into sub-paragraphs, each of which refers to a different application domain. Focusing on urban goods distribution, the problems tackled in the selected literature reported in the next sections, can be considered as the last piece of a general framework for freight transport model.

3.1. Tactical-operative city logistics measure assessment

Agent-Based Simulation has been used to evaluate some tactical-operative city logistics measures such as freight consolidation, tolls, time windows, and delivery parking management, already adopted or planned to be so in a city.

In Tamagawa et al. (2010) the proposed model is bi-level, where the first level is the learning model (the objective is to minimize the Q-learning function, specified for each class of agents), and the second level is a vehicle routing problem with forecasted time windows (the objective is to minimize total transport costs). Five classes of agents are considered: freight carriers, shippers, residents, administrators and motorway operators, which operate in a competitive manner, each with its own objective. The authors provide the Q-learning function for the carriers, imposing that the Q-value is the profit, assumed as the difference between the fee for the shipper and the transport cost (obtained from vehicle routing). A small experiment for a test road network is proposed by simulating the case where two city logistic measures, road pricing and bans on trucks weighing more than 10 tons, are adopted.

Freight consolidation is a measure often treated in city logistics, where one of the aims is to minimize the number of vehicles used for urban freight transport. Anand et al. (2014) propose a study which deals with the load consolidation of different shippers and carriers within the same vehicles. The agents considered belong to five classes. The person agents are the end-consumers of freight (choosing trips and quantities to purchase). The shop agents are the shopkeepers (retailers) who take decisions on orders and shop inventory management. The shipper agent supplies the shopkeepers (the authors assume one only shipper type with the freight always available in the warehouse). The carrier agent is an actor who provides the freight delivery service (for retail supply independent carriers for freight delivery are considered). The administrator agent is the municipality which manages freight activities for economic and environmental sustainability. An objective function is provided for agents who interact with one another in terms of freight, money, information and external effects. The authors provide an example (a toy model) defining a collaborative scenario where some agents collaborate in order to synchronize their activities and reduce the negative impacts on the city (as stated above, the proposed scenario deals with load consolidation).

Baykasoglu and Kaplanoglu (2011) examine the case of load consolidation in freight operations, formulating a multi-agent based decision-making approach: the agents involved in the process make load consolidation decisions collaboratively. However, the process being based on profit, a consolidation order can be rejected. In this case a negotiation phase is started to try to fulfill it.

Focusing again on delivery, to model this aspect in the special case of electric freight vehicles, Boussier et al. (2009) propose a virtual framework where stopping places are shared between freight vehicles and private cars. The aim is to analyze the impacts due to the reservation of stopping places, to park or to deliver, for electric freight vehicles. The methodology evaluates the measures able to improve efficiency in freight transportation.

3.2. UDC effect assessment

To simulate the impacts due to the introduction of an UDC, Van Duin et al. (2012) propose an approach based on multi-agent modeling which incorporates the vehicle routing problem (starting from the urban distribution center) solved with a genetic algorithm. The model system is applied, with the model being used to evaluate how the increase in UDC usage affects the environment. The scenario provided considers a dynamic fee for the use of the UDC. In order to encourage its usage the fee decreases when the opportunity to combine the load efficiently increases.

To evaluate the effectiveness and the viability of an urban distribution center, Teo et al. (2015) propose a multi-agent modeling system integrated with a geographical information system. Two types of agents are considered: the UDC operator, whose objective is profit maximization, and the carrier, whose objective is cost minimization. For each agent a learning function is defined: for the former it concerns profit, for the latter it refers to costs. A test application with one UDC operator and four carriers is provided.

Wangapisit et al. (2014) propose a Multi-Agent System (MAS) model for evaluating jointly the delivery system and freight vehicle parking management. The proposed model framework considers both a vehicle routing problem (also starting from an urban distribution center), and interaction among some stakeholders (in a cooperative context) with a reinforcement learning model. The proposed MAS considers six types of agents, each with a specific objective (Table A.1). Specifically, the authors identify two types of carriers: freight carriers are those that deliver freight to the UDC; neutral carriers are those that deliver freight from the UDC to shop-owners and residents. An experiment, considering a small test network, is proposed in a scenario when administrator, freight carriers and neutral carriers collaborate to deliver the freight in the city. The city logistic measures tested are the use of the UDC and parking management for freight vehicles.

3.3. Access management

An effective measure to manage access in some areas of a city is to impose a toll upon vehicles. Teo et al. (2012 a&b) propose a multi-agent system model (with reinforced learning) combined with a vehicle routing problem to explore the behavior of stakeholders in urban freight distribution with respect to e-commerce in the presence of a toll system. The learning function specified for administrator agent deals with pollutant emissions. The authors extend the coverage by Teo et al. (2014) to consider all carriers (not only those dealing with e-commerce) moving in the city for freight distribution and introduce the motorway agent (his objective is profit maximization).

van Heeswijk et al. (2016) develop an agent-based simulation framework to evaluate a set of urban logistics policies (namely road pricing, parking fees, and access limitations), considering five types of agents with a collaborative approach. To include cooperation in the model, the authors group some agents into a coalition (a condition to define a stable coalition is that the coalition can improve the system performance if compared to the case in which agents play individually), defining a single objective function. Moreover, because each coalition requires rational agents that cooperate, a gain-sharing mechanism is introduced in the model.

A model to simulate urban freight distribution by varying traffic conditions and policy measures (namely road pricing and access restrictions) is proposed in Schroeder et al. (2012). The authors introduce a model with two types of agents: transport service providers (organizers of the transport chain) and the carriers (who obtain contracts from transport service providers for transport services, choosing the transport mode and designing vehicle routing and scheduling). The model is tested on a toy network, with one transport service provider and four carriers.

In order to simulate the effects of introducing transport policy measures (i.e. tolls) in a city, Schroeder and Liedtke (2017) propose an agent-based simulation framework where both carriers and other vehicle drivers are considered as agents. Each agent type plays with a specific objective function in order to maximize his/her utility when interacting with the other agents.

As aforementioned, often the agent-based simulation models are coupled with other models trying to better simulate the reality. In this way, Le Pira et al. (2017) propose a combination between discrete choice models and agent-based models to evaluate the willingness to accept new policies (i.e. zone access limitations, access fees, time windows) from the stakeholders involved in the urban freight transport. The agents considered are the retailers, the transport providers and own account transport operators (such as own-account retailers). For each agent a utility function is specified in the discrete choice model determining the initial status of the agent. The status can change when the agent considers alternative policies.

3.4. Vehicle routing problems

In order to simulate the interactions between retailers and truck drivers in a dynamic and uncertain environment, Sopha et al. (2016) propose an ABS to solve dynamic vehicle routing, where the dynamic implies variation in the freight demand. Two types of agents are considered: retailers and truck drivers. The optimization problem is formulated in terms of traveled distance minimization. Retailer behavior is simulated with a lateness tolerance which is used as a constraint of the vehicle routing problem. The search algorithm for vehicle routes is the particle swarm.

4. Conclusions

Agent-Based Simulation (ABS) for freight distribution simulation appears to be both a challenge and an opportunity for future developments in this research field. Various stakeholders are involved in urban freight distribution and ABS allows many types of agents to be considered, each with its specific objective function (max profit, min cost, …), behavior (cooperative or competitive), specific characteristics, needs and aspirations. In this simulation approach, an (intelligent) agent who operates to achieve one (or more) objective, following some criteria, interacting with other agents and learning from his/her experience, represents a stakeholder.

In this paper, we sought to classify the current literature on agent-based simulation in urban goods distribution by following some homogeneity criteria. A set of six criteria (application domain, simulation impacts, type of agents, agent behavioral, type of model, type of application) was defined, choosing the *application domain* as the main strand to categorize the literature.

From the analyzed papers, it emerged that the effects of a broad set of city logistics measures (UDC usage, parking management, load consolidation, ….) can be assessed and that the research methods in this field are advancing, often coupling agent-based simulation with another model (such as vehicle routing).

This field of inquiry, developed in the last ten years, does not yet appear to have reached full maturity. Applications are carried out only on test cases, considering small study areas and a limited number of agents, without considering applications in real cases. The reason may well lie in the fact that such detailed simulation requires a large amount of data, often difficult to find.

Several theoretical issues remain a matter for in-depth research: better understanding of the decisional processes of the agents, better simulation of the information effects on agent actions, specification of more advanced choice models and improvement in their relative learning processes.

Appendix A. Classified papers

Table A.1- Literature review

Paper	Application Domain	Simulation impacts	Type of agents	Agent behavioral				Type of Application
				Cooperative	Competitive	Agent interactions	Objective function	
Tamagawa et al., 2010	Road pricing Truck ban	Environmental Economic Social	• Freight carriers • Shippers • Residents • Administrators • Motorway operators		X	X	• Max transport profit • Min of transport costs • Min emissions • Min complaints • Max toll revenue	Test road network
Anand et al., 2014	Load consolidation of different shippers and carriers within the same vehicles	Environmental Economic Social	• Person agent • Shop agent • Shipper agent • Carrier agent • Administrator agent	X		X	• Max utility • Max profit • Min cost • Min cost • Min impacts	Toy model
Baykasoglu and Kaplanoglu, 2011	Load consolidation method selection	Economic	• Order agents • Truck agents • Regional load consolidation agent	X		X	• Min cost • Min operation cost • Max profit	Benchmark problems
Van Duin et al., 2012	UDC usage UDC fee	Environmental Economic Social	• Freight carrier • Terminal agent • Truck drivers • Streets & nodes • Retailers • Municipality		X		• Min cost • Min cost • Min distance • N.A. • N.A. • Min emissions	Test application
Teo et al., 2015	UDC effectiveness and viability	Economic	• UDC operator • Carrier		X	X	• Max profit • Min cost	Test application

Paper	Application Domain	Simulation impacts	Type of agents	Agent behavioral				Type of Application
				Cooperative	Competitive	Agent interactions	Objective function	
Wangapisit et al., 2014	UDC Parking management	Environmental Economic	• Freight carriers • Neutral carriers • Shop owners • Residents • Administrators • Logistics association	X		X	• Min operation cost • Min operation cost • Min delivery cost • Min emissions • Min complains • Max use of UDC	Test network
Boussier et al., 2009	Parking management	Environmental	• Retailers • Private cars • Freight vehicles • Control agent • Stopping space	X			Not provided	Virtual simulation
Teo et al., 2012a&b	Road pricing	Environmental	• Freight carriers • Shippers • Residents • Administrators		X	X	• Max transport profit • Min of transport costs • Min emissions • Min complaints	Simulation study (only e-commerce)
Teo et al., 2014	Road pricing	Environmental	• Freight carriers • Shippers • Residents • Administrators • Motorway operators		X	X	• Max transport profit • Min of transport costs • Min emissions • Min complaints • Max toll revenue	Simulation study
van Heeswijk et al., 2016	Road pricing Parking fees Zone access Time access restrictions	Economic Environmental	• Receivers • Shippers • Carriers • UCC operators • Administrators	X		X	• N.A. • Min costs • Max profit • Max profit • N.A.	Virtual network
Schroeder et al., 2012	Road pricing Access restrictions	Economic	• Transport service providers • Carriers	X			• Best price • Min costs	Proof-of-concept
Schroeder and Liedtke, 2017	Toll assessment	Economic	• Passengers • Carriers		X	X	• Max Utility • Min Costs	Test application on grid network

Paper	Application Domain	Simulation impacts	Type of agents	Agent behavioral				Type of Application
				Cooperative	Competitive	Agent interactions	Objective function	
Le Pira et al., 2017	Zone access Access fees Time windows	Economic	• Retailers • Transport providers • Own account transport operators	X	X	X	• Max utility • Max utility • Max utility	Test application
Sopha et al., 2016	Dynamic vehicle routing simulation	Economic	• Retailers • Trucks	X			• - • Min distance	Test instances

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