ENGLISH VERSION

Concepts for modeling road asset management systems using agent-based simulation

Conceptos para la modelación de sistemas de gestión de activos viales usando simulación basada en agentes

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Abstract

Complex emergent and adaptive systems raise modeling challenges that cannot always be faced through mathematical modeling. The agent-based simulation is a simulation technique of socio-technical systems that allows modeling the interactions among agents, thereby offering an emergent alternative to the development of road infrastructure management systems. Road infrastructure management is a socio-technical system similar to open and adaptive systems, because there is interaction among the agents (state, private and public); it needs to consider the variability through the risk inclusion and it induces externalities that modify the system's initial conditions. This paper discusses the agent-based simulation and how it can be used for designing road asset management systems. Therefore, a generic model is proposed, based on the existing literature, in order to characterize the types of agents involved. A plan is also discussed to include the risks in the infrastructure asset management under the agent-based simulation system. It was concluded that this modeling approach allows incorporating the effect of the agents' decisions on maintenance planning, and the same time it has enough flexibility to include other effects, such as uncertainty and risk, considering that an asset management system is an open socio-technical system and not necessarily a closed mechanistic system

Keywords: *Simulation, agent, agent-based simulation, road asset management, risk*

Resumen

Los sistemas adaptativos complejos y emergentes plantean desafíos de modelación que no siempre pueden enfrentarse mediante modelación matemática. La simulación basada en agentes es una técnica de simulación de sistemas socio-técnicos que permite modelar las interacciones entre agentes, ofreciendo una alternativa emergente al desarrollo de sistemas de gestión de infraestructura vial. La gestión de infraestructura vial es un sistema socio-técnico con rasgos de sistema abierto y adaptativo, puesto que existe interacción entre agentes (estado, privados y publico), necesita incluir la variabilidad a través de la inclusión de los riesgos, y genera externalidades que modifican las condiciones iniciales sobre las cuales opera el sistema. Este trabajo se discute la técnica de simulación basada en agentes y cómo esta se incorpora en el diseño de sistemas de gestión de activos viales. Se plantea un modelo genérico para la gestión de infraestructura vial, en base a la escasa literatura que existe sobre el tema, para posteriormente caracterizar los tipos de agentes involucrados. Se discute también un esquema para incluir los riesgos en la gestión de activos viales bajo el enfoque de simulación basada en agentes. Se concluyó que este enfoque de modelación permite incorporar el efecto de las decisiones de los agentes sobre la planificación del mantenimiento y a la vez que posee la suficiente flexibilidad para incorporar otros efectos tales como la incertidumbre y el riesgo, tomando como base que un sistema de gestión de activos es un sistema abierto de carácter socio-técnico más que un sistema cerrado mecanicista

Palabras clave: Simulación, agentes, simulación basada en agentes, gestión de activos viales, riesgo

1. Introduction

Road assets are the physical elements, technological processes and data systems that allow the road infrastructure to provide an adequate service to the users with a certain degree of quality. The infrastructure is a subset of road assets. On the other hand, the purpose of road asset management is to preserve it, so that the offered service level is consistent with that expected by direct and indirect users and non-users, subject to the available budget.

Traditionally, road asset management has been focused on pavement and bridge management, assuming that these assets have the greatest value, the most relevant ones to give continuity to the road infrastructure, and that the provided service level is adequate for users. Likewise, it anticipates that context conditions do not change, which allows estimating the progression of the demand and of the infrastructure's behavior under pretty much stable performance laws. Thus, the management process acts as a close system, which defines maintenance plans and schedules based on technical criteria that solely determine the service level offer.

The traditional approach presents difficulties in the optimization of the plans when the benefits of reducing the gap between the provided and expected service levels are analyzed. The fact of dealing with the management process as a closed and mechanistic system further contributes to this; in other words, it lacks the capability to interact with the context environmental conditions as well as the capability to include uncertainty (risks) and how this changes the decisions of users, analysts and decision-makers.

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For example, when management systems do not include the uncertainty they are incapable of analyzing how the maintenance investment planning changes whenever structural changes in the economy occur, which impairs the traffic demand temporarily and spatially. Likewise, it does not allow foreseeing how a maintenance plan changes when disruptive events occur, such as natural and anthropic events or climate change. Furthermore, it neither allows incorporating travel (or non-travel) decisions of different types of users nor knowing how useful it is for them to reduce the gap between provided and expected service levels. The agent-based simulation is an emergent branch of simulation coming from the social sciences, but it allows solving the problems of traditional techniques intended for asset management, because it incorporates the concept of socio-technical systems, where different agents (actors) are also included in the decision making process.

Thus, the purpose of this work is to discuss a new modeling concept applied to the design of road asset management systems, which adds to the traditional modeling the notion of open, adaptive and emergent system, and the actors or agents as members of a decisional group. This approach offers the advantage of capturing more efficiently the benefits, but also the externalities, produced during an asset management process, and at the same time, of incorporating the uncertainty associated to the agents' behavior. First, the paper describes the simulation concept, specifically the agent-based simulation, as well as the concept of agent itself. Next, it discusses the application of the concept to the design of road asset management systems. It starts by reviewing the literature and then it conceptually develops an asset management system, which allows identifying the agents and their characteristics. Next, it analyzes the effects of incorporating the risks (natural and anthropic) to the asset management, in accordance with the agent-based simulation system. Finally, it presents the conclusions thereof.

2. The agent-based simulation

Simulation is a way of modeling reality, based on recreating rules that represent the real world. Its main advantage as a modeling instrument is that it allows representing complex relationships among entities where analytical (mechanistic) models cannot or are insufficient to reflect all interactions. Likewise, it allows representing systems and their interactions, prove multiple hypothesis simultaneously and make predictions under multiple conditions. Figure 1 shows the architecture of a generic and independent model of the simulation technique.

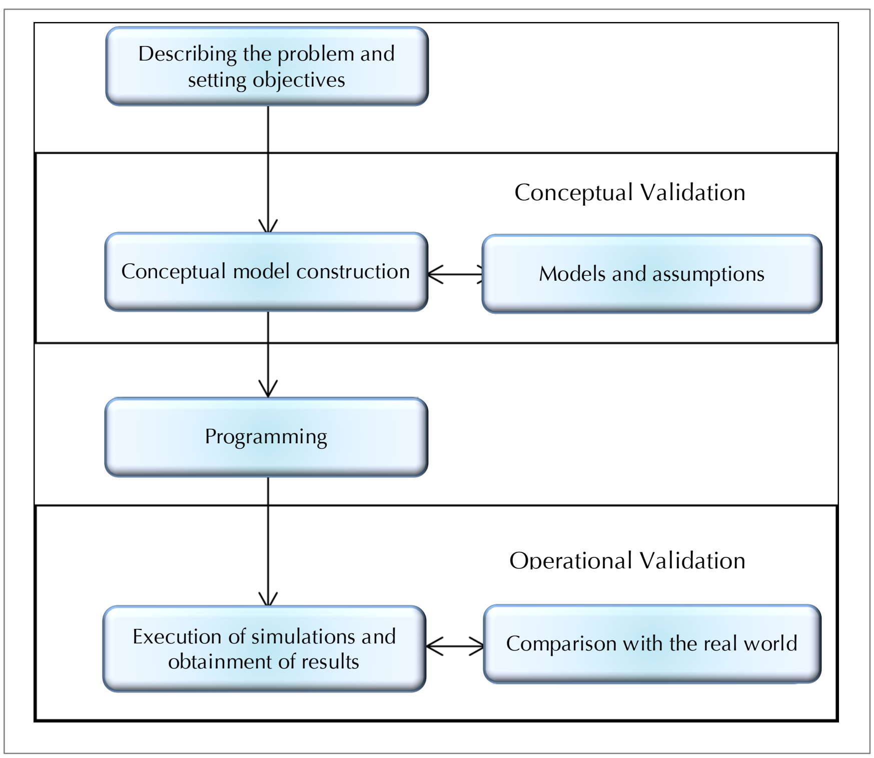

Figure 1. *Diagram of a generic simulation model (Heath et al., 2009)*

Currently, the main simulation methods are: discrete-event simulation, dynamic system simulation and agent-based simulation. The present paper deals with the latter. Figure 2 illustrates the scope of action of the three simulation techniques previously mentioned. It can be observed that the agent-based simulation can be used with all levels of details, therefore, it offers more versatility than the other two simulation techniques.

The key element of the agent-based simulation is the "agent", although there is no universal definition for this term, it may refer to a component of a system or autonomous entity, for example, people playing different roles (consumers, citizens, patients, doctors, clients), equipment (vehicles, cars, cranes, trains, airplanes, machines), non-material things (projects, products, ideas, innovations) and organizations (companies, political associations, countries, public utilities) (Grigoryev, 2015). In any of these cases, agents are programed to make decisions and react when faced to changes in the system in which they are involved, and to interact among them. Programming is based on pre-defined rules ranging from pre-program reactions to complex decisions based on artificial intelligence. Further on there is a deeper analysis of the concept of agent.

The agent-based simulation models dynamic processes and interactions among agents, which are repeatedly simulated. Historically, the capability of the agents to adapt themselves and use models that allow predicting the future has been used for modeling and predicting the behavior of complex adaptive systems and socio-technical systems, in the understanding that these systems have a large number of agents and decision makers with disperse control, and many organizational levels. This simulation diagram starts with the definition of individual actors (the agents) and then defines their interactions, which, as a whole, generate system-based interactions. Figure 3 shows an abstraction of a complex system with emergent properties, where the behavior of the agents and the interactions among them and the environment lead to a complex and emergent system.

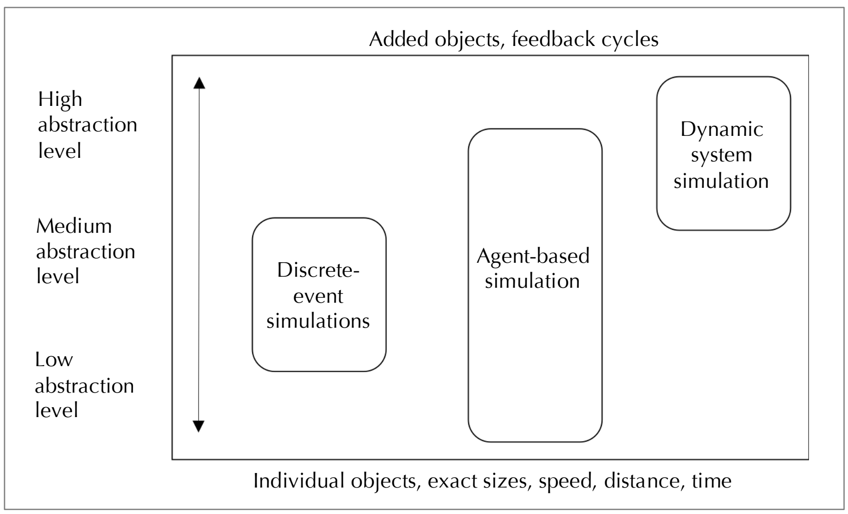

Figure 2. *Level of detail of the different simulation techniques (Grigoryev, 2015)*

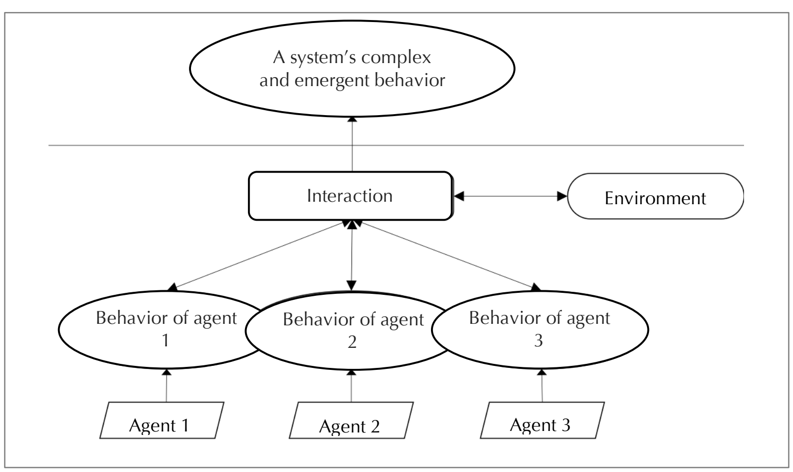

Figure 3. *Diagram of an agent-based complex system (Sanford, 2007)*

The agent-based simulation is a tool used mainly for modeling adaptive, emergent, open or closed systems, where there is an interaction between technical decisions and agents making the decisions in response of those technical decisions. According to (Zhang y Li, 2010), an agent-based model requires an environment where agents can develop their activities, so that the implication of the decisions and interactions among agents have an impact on that environment. In terms of simulation, this environment could be a network, a geographical representation, a grid or a non-spatial projection. Decisions and interactions among agents are given within a context that defines the semantics of the interactions. In simple terms, Figure 4 shows how the agent-based simulation expresses the real world in a simulation environment by either a unidimensional or multidimensional projection.

In the following situations it is better to use the agent-based simulation rather than the equation-based modeling for analyzing complex and adaptive systems (Axtell, 2000; Singh y Gupta, 2009):

- *When a mathematical model can be formulated, but it can only be solved partially*
- *When mathematical models have such complexity that they are unsolvable*
- *When explicit numerical realizations cannot be made*

The following is a standard procedure for developing agent-based simulation models of socio-technical systems (Nikolik y Ghorbani, 2011):

- *Analysis of the system, by defining the problem and identifying those who are affected by the problems; identification of the system regarding its internal structure and potential interaction with an external system (exterior world or environment in which they live); conceptualization of the system followed by a formalization of the system's ontology.*
- *Design of the model, by defining its structure through the identification of the entities composing its boundaries, behavior of the agents (active, proactive, reactive), ability to interact and the links among them; and by identifying the behavior of the model's entities.*
- *Detailed design of the model, in terms of the model's logic formalization, and the experimental design. The latter considers, based on a modeling hypothesis, the number and type of model to be run, the simulation scenario and the sensibility of parameters.*
- *Implementation in the software, which basically consists in loading codes in the ad-hoc or commercial software.*
- *Evaluation of the model, consisting in the verification of the types and input data classified in action data, knowledge data and their relationship with the physical and social domains. Nikolok and Ghorbani (8) also recommend a scaled verification where agents are individually analyzed, then the interactions limited to the base model and the multi-agent verification are analyzed. Finally, the model's validation is made, followed by experimentation and analysis.*

The most frequent applications are found in the field of social sciences, biology, negotiation, and evaluation of public policies. In engineering, it is mainly used to model chains of supply, but there is also evidence of applications in traffic engineering, transport planning, constructive processes and construction management in general. On the contrary, concerning the infrastructure management there is little evidence and in the case of risk assessment, this technique is basically applied in modeling evacuation systems.

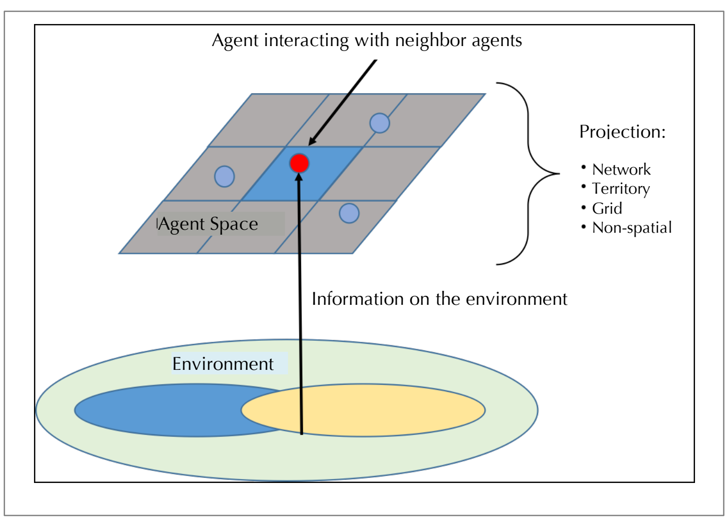

Figure 4. *From real environment to simulated environment (Macal y North, 2010)*

3. The agent concept

In general terms, an agent is an entity or component of a system that is capable to perceive and act on its own and decide what to do in order to reach its goals (Clymer, 2009). It has the capability to model from a simple element to more complex ones, such as the behavior of decision makers. A complete definition of the term considers the agent as an entity with the following attributes (Macal y North, 2009):

- An identifiable, self-contained and discrete entity, which has a set of characteristics and rules governing its behavior and capability to make decisions. The discrete character implies that the agent has a defined boundary that allows to clearly distinguish it from another agent.
- A living, localized entity that interacts with other agents and within its environment, through interaction and communication protocols; it also has the capability to respond to the changes in the environment.
- An autonomous and self-directed entity that can function independently.
- A flexible entity having the ability to learn and adapt its behavior based on accumulated experience, which requires to have memory. Thus, it may have rules that modify its own rules of behavior.

These attributes can be complemented by the previous characterization defining them as an autonomous entity that makes decisions (Bonabeau, 2002). Each agent individually evaluates different situations and makes decisions based on rules, showing different behaviors according to its environment. Behaviors are originated in actions with repetitive character, programmed and interactive with the actions of other agents, thus creating emergent behavior patterns.

The behavior of the agents is individual and non-linear, characterized by 'if-then' rules or non-linear coupling of actions among agents. Agents have memory, dependence on other agents, learning ability and adaptation skills. They are also reactive (it perceives and reacts to change in the environment), proactive (it executes a series a tasks to reach goals) and social (because it interacts with other agents to resolve conflicts or to collaborate).

4. The agent-based simulation for road asset management

There is recent evidence in the literature addressing the use of this type of technique to model road asset management, among which the works described in (Sanford y McNeil, 2008; Moore et al., 2008; Osman, 2012 y Batouli y Mostafavi, 2014; Bush et al., 2014a y Bush et al., 2014b are worth highlighting. These references discuss at a conceptual level the applications of agent-based modeling to transport asset management problems, which are useful to characterize the agents involved therein. Batouli and Mostafavi (2014) conceptualize a multi-agent asset management model, as seen in Figure 5, which includes the management agency, the users and road assets. Sanford and McNeil (2008), Moore et al. (2008) and Osman (2012) describe the management agency in terms of road authority and decision makers, in order to incorporate in the model the goals of the infrastructure policy at a national level.

It is important to make these distinctions, since an adequate characterization of the agents necessarily requires to define the model's goals and boundaries first, and then characterize the agents. Otherwise, there is a true possibility of leaving out relevant agents. On the other hand, it is important to characterize the management cycle with the aim of temporarily incorporating the distinction between agents and the activation of their engagements in the management process. Concerning the size of an asset management system, they can be specified from a bigger one to a smaller one, as follows:

- Asset Management including policy decisions (Sanford y McNeil, 2008; Batouli y Mostafavi, 2014)
- Asset Management including policy decisions (Osman, 2012)
- Pavement Management (Moore et al., 2008)
- Bridge Management (Bush et al., 2014a; Bush et al., 2014b)

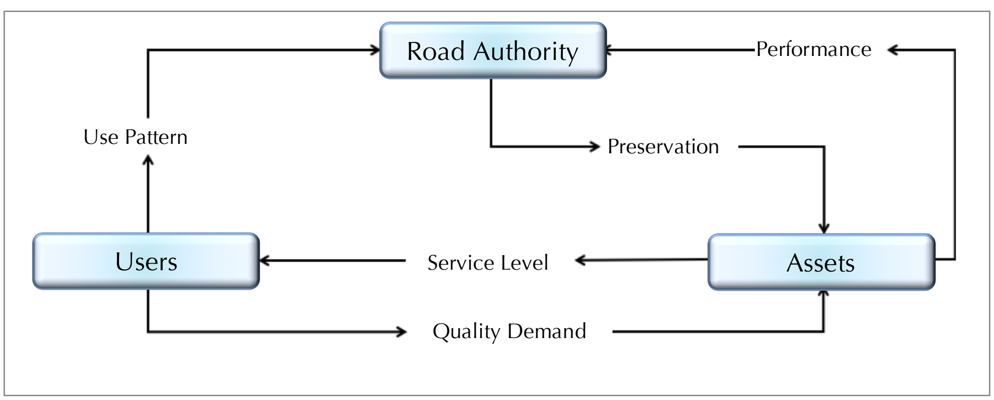

Figure 5. *Asset management concept under normal operating conditions (Moore et al.,2008; Batouli y Mostafavi, 2014)*

In Figure 5, the road authority is in charge of measuring the performance of the assets, designing and applying the preservation measures, according to the use pattern of the infrastructure and the preservation activities promoted by the road authority. This approach is comparable to a process of allocating financial resources with a budgetary constraint. It can be extended if the decision making process of the road authority is expanded, in which case it is necessary to characterize the optimization process, and indicate whether the citizen involvement is included in the resources' allocation system under the Public, Private, People, Partnership (4P) model.

Batouli y Mostafavi (2014), suggest that modeling of the decision making process of the road authority and the users' behavior can be done through the agent-based simulation; instead, the modeling of the assets' performance requires the use of traditional behavior models. In general, assets are the easiest agent to represent if asset performance models are available (Sanford y McNeil, 2008; Osman, 2012). According to Figure 6, it is possible to establish a generic classification of the agents and determine which characteristics they must consider. Generic agents are: the users, the road authority and the infrastructure. These agents may further include the companies executing the maintenance tasks, which range from those of the road agency itself (in the case of direct administration) to those considering the maintenance concession. In this case, Figure 6 has an additional component in relation to Figure 5. Keeping this in mind, it is possible to propose the agent classification in Table 1.

Table 1 shows that three agents make decisions during the management tasks' application: the road authority, the users and the maintenance agency. For example, the agent-based modeling allows describing the decision making processes of the agents within the organization and how they impact on the service level that the road authority wants to provide. On the other hand, the users, as receptors of the service level, also react and make decisions of different nature, based on the service level they expect from the network. In this way, it is possible to specify a useful function for the society, in terms of the service level, as expressed in Equation 1, where the service level is explained by the agents.

Usefulness = Offered Service Level – Demanded Service Level **(1)**

In turn, the minimum usefulness corresponds to that tolerated by the agents (Osman, 2012):

Usefulness **>** *Minimum tolerated usefulness* **(2)**

Maintenance tasks are executed by the maintenance agency, therefore the outcome of their work necessarily affects the outcome that the road authority offers to the people. Likewise, the outcome of maintenance tasks depends on the agency's organizational system, on its interaction with the market that provides the supplies, machinery and labor that they need, as well as on the contractual interaction with the road authority.

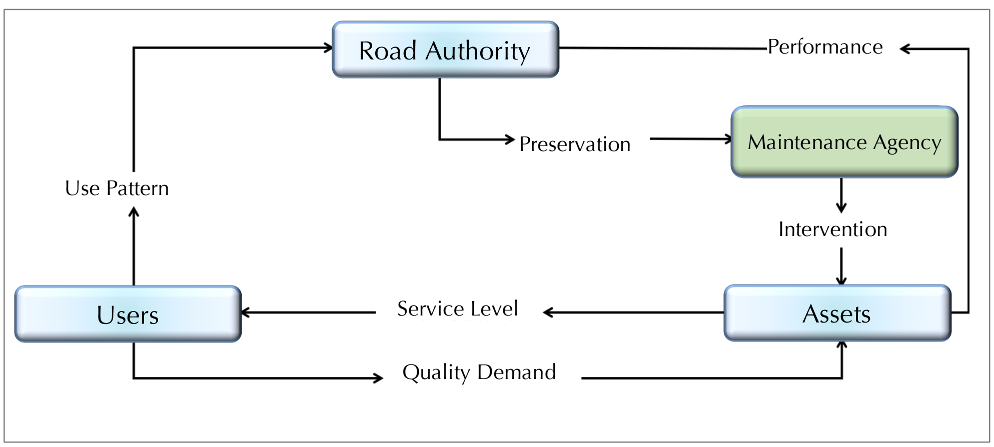

Figure 6. *Generic concept of asset management including maintenance contracting under normal conditions*

Table 1. *Agent classification (Sanford y McNeil, 2008; Osman, 2012)*

Agent	Action executed by the agent	Generic Attribute		
		Static	Time-Dependent	Time-Dependent and Action-Dependent
Road Authority	• Executes interventions • Evaluates user's response • Evaluates condition of road assets	• Intervention plan • Service level • Risk level	• None	• Budget allocation
Users	• Uses infrastructure services • Uses other facilities • Evaluates quality • Uses a type of vehicle • Makes travel decisions	• Type of user • Income level • Service level expectation • Risk acceptability	• None	• Satisfaction level • User costs
Road Assets	• Does not execute any action	• Physical characteristics • Localization • Deterioration rate • Age	• Environmentatt ributes	• Condition • Current service level • Service standard • Risk
Maintenance Agency	• Applies maintenance operations	• None	• Experience	• Maintenance rules • Budget

Table 1 also describes the attributes that agents undertake, classifying them in static, time-dependent, and time-dependent and action-dependent. Static attributes do not change over time and do not depend on decisions that agents make. For example, in the case of the road network, attributes are mainly static in the short and medium term. Attributes depending on time and decisions vary as the interactions among agents occur and they contribute to the modeled system with the emergency and complexity condition.

5. The incorporation of risk

Risks are a relevant aspect that is usually not considered in road asset management systems. In simple terms, risk is defined as the probability that a threat or natural or anthropic danger negatively affects a system, so as to partially or totally compromise its operation. For example, the probability that an earthquake limits the operation of a port system. The agent-based modeling can explicitly incorporate them, thereby generating multiple change scenarios that can modify the choice of the optimal maintenance plans. The advantage of this modeling system is that it allows evaluating and comparing multiple uncertain conditions, which provides a unique flexibility to the analysis.

In general, the reviewed literature does not give a detailed account of the cascade effect associated to the total or partial interruption of the network due to natural or anthropic threats that can alter the assumptions on which the maintenance plans and schedules rely. Only (Hasan y Foliente, 2015 broadly explains that these effects imply the incorporation of additional agents to those described in the previous section and that the agent-based modeling is useful to include this effect in the conceptualization of a model like the one proposed herein. With the purpose of simplifying the model, it is preliminarily assumed that:

- *It does not consider cascade effects, that is, the second or third turn impacts that can be induced on other infrastructure systems or other social systems, with the aim of reducing the number of agents and the size of the system.*
- *The general approach is that of a risk management system focused on infrastructure, in order to control the size of the system and the subject of study.*
- *Three management scales are assumed: prevention, emergencies and disasters, since each one requires different actions from the agents. In the preventive case, actions are focused on maintenance planning in order to increase the infrastructure's resilience. Regarding the emergencies, actions are focused on immediate responses and the development of restoring interventions or resilience increase of the road infrastructure.*
- *In relation to disasters, the immediate response, the provision of evacuation infrastructure and the development of restoring interventions or increase of the medium-term resilience, which eventually imply the intervention on other type of infrastructures or other types of systems.*

- *The analysis uses a management approach based on needs, with the aim of preventing the use of long-run predictive models. This enables the possibility of a time window that is sufficiently long to analyze before/after effects and sufficiently short at the same time.*

Considering the aforementioned aspects, a risk management generic model considers 5 groups of agents: threats, road assets, users, road authority, and maintenance companies. Thus, users will determine the tolerable risk levels. The road authority, which considers threats and road assets, will determine the investment conditions to harmonize the risk's objective assessment with the risk's expected level, by applying maintenance contracts implemented by maintenance companies, which in turn seek to maximize their benefits. Figure 7 shows this concept in a diagram illustrating the agents and the goals pursued by each one of them.

In Figure 7, the central agent is road assets, which determine the risk level. This risk level, which determines the investments, establishes 2 conditions: on the one hand, the users determine the admissible or tolerable risk level depending on their goals; these goals differ depending on whether the users are individuals, load or passengers. On the other hand, the road authority estimates, by means of some type of model, the "offered" risk level as a service standard.

Eventually, this estimate includes the users' indirect feedback though the interaction between the offered service level and the quality degree expected by users. The analysis of the upper part of Figure 7 shows that users use road assets and at the time evaluate, according to their expectations, the operation of these road assets, both under normal operating conditions and under emergency situations.

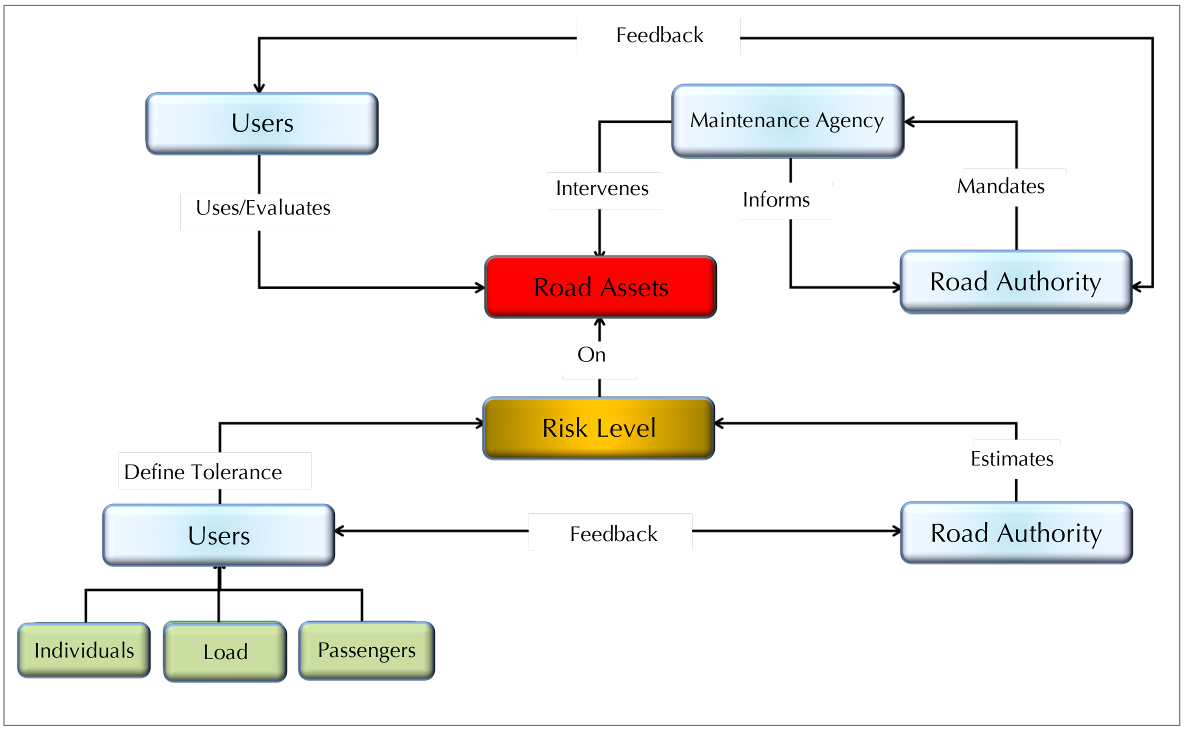

Figure 7. *Interaction among agents in a management risk context of a road infrastructure management system*

6. Conclusions

The purpose of this work was to discuss, at the conceptual level, the agent-based simulation approach and how it could be used to model a road asset management system in the presence of risks and uncertainty. The following conclusions were derived from this discussion:

- *The traditional road asset management systems are modeled as closed systems that do not allow incorporating the users' decisions, nor the uncertainty or the risks; therefore they lack the means to determine the consistency between the service levels provided and those demanded by users.*
- *The agent-based simulation is a technique that enables the analysis of complex, open and emergent systems, including the agent as a key element, which is capable to make decisions, interact with the environment and other agents, make decisions and learn, thereby giving a flexibility degree that allows analyzing multiple possible scenarios.*
- *The existing literature on the subject is recent and addresses mainly conceptual aspects dealing with how to use the agent-based simulation to model pavement and bridge management systems, and the incorporation of decision makers. A relevant aspect that should be highlighted is that this approach must be necessarily integrated to the traditional techniques to model the behavior of road infrastructure over time.*
- *In the standard asset management system, the main agent is the road authority, the users, the infrastructure and the agency executing the maintenance works. The application of the agent-based simulation seeks to maximize the usefulness of the agents, expressed as the minimum difference between the offered service level and the expected one, under the condition that this usefulness is higher than the minimum usefulness.*
- *The incorporation of risk in the agent-based road asset management must consider the cascade effects resulting from the interaction between road works and other infrastructures, in addition to the modeling scope: prevention, emergencies and disasters. This determines the actions taken by the agents.*
- *The agent-based simulation is a promising tool for developing road asset management systems involving people's decisions at different levels and scopes, ranging from policy decisions (decision makers) to travel decisions by users. Thereby, the socio-technical character of this type of systems comes up naturally. As a tool, it allows evaluating people's usefulness dimensions that serve as a complement to the economic assessment, thus improving the quality of the maintenance plans.*

7. Acknowledgements

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