Spatial and Cognitive Simulation with Multi-agent Systems

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Abstract. The simulation of human behavior in space is an extremely interesting and powerful research method to advance our understanding of human spatial cognition and the interaction of human beings with the environment. Multi-agent systems are an emerging computing paradigm for the construction of such simulations. During the last two years, we have used multi-agent simulations for three different investigations of spatial and cognitive questions:

- use of signage in airports to guide travelers to the gate,
- communication with maps,
- linkage between physical reality and the cadastral (legal) system.

In this paper we will report on these efforts. We first discuss the concept of multi-agent systems and explain the special type of multi-agent system used for simulation of cognitive and spatial situations. The following three sections each review one of the three simulations we have constructed. The last section identifies the similarities in these approaches and lists questions we hope to investigate in the future with this method.

Keywords. Spatial cognition, multi-agent simulation, computational models

1 Introduction

Multi-agent systems are an emerging conceptual paradigm to simulate the interaction of multiple autonomous agents in an environment [28, 29]. Multi-agent systems have many applications; our interest is in their use to build computational models of independent cognizing agents in a spatial environment. In general, a system is called multi-agent if the system contains at least one agent that perceives a simulated environment through some sensors, and its actions influence the environment and are influenced by the perceived situation in the environment (Figure 1). The various types of multi-agent systems are discussed in Section 2.

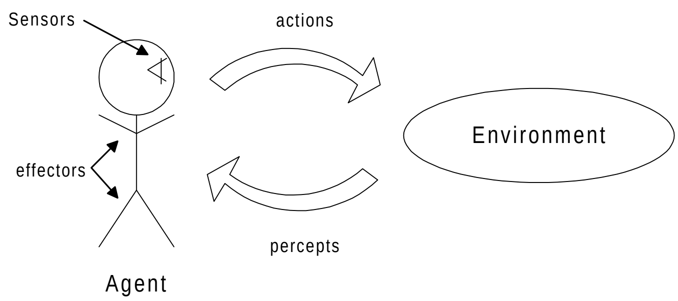

Fig. 1. Agent in the environment

Computational models are a very powerful tool for the description and modelization of spatial and cognitive processes. Computational models are often used by scientists to describe in a succinct and objective way the results of their analysis. They can be applied to predict situations and are therefore useful in engineering to check the design of new systems. We are interested in building computational models because they help us to bridge the gap from pure research to applications.

Computational models are used in many parts of science; they originate in physics, but are increasingly used in the social and cognitive sciences [7]. Various examples of computational models for spatial cognition have been presented in the COSIT conferences [1, 22]. We have recently built three computational models in three core areas of spatial theory, namely wayfinding, communication with maps and real estate registration systems. From these applications we see a generalized type of "spatial simulation with multiple cognizing agents" emerge.

1. Wayfinding is a classical part of spatial theory and there is numerous literature [14]; different aspects are explored, very often concentrating on the process of learning a spatial environment. We focused on the alternative situation where one navigates an unfamiliar environment based on signs available and we were particularly interested in situations like airports, where the traveler has no intentions to learn the environment [23, 24].
2. The assessment of the quality of maps is an often-discussed question, where very often considerations of esthetics and personal preferences for certain styles influence the judgment. We were interested in constructing a situation for assessing maps based on their suitability for a determined task, for example, to navigate in an unknown city. To lift the discussion to a theoretical level, we attempted to construct a computational model of map making and map use, in which the suitability of the produced map for a clearly identified task can be discussed [9].
3. Property registries, e.g., cadastres in Europe, protect the ownership rights of people in land. There is a complex interaction between surveyors, which map the properties, the owners, who buy and sell land, and the registry, courts and sheriffs, which enforce the rules. For application in the Reform Countries in Eastern Europe, new cadastral systems are designed and we realized that our understanding of the interplay between the participants is not sufficient to guide our designs [10]. Therefore the construction of a computational model was started [2].

We found that these three computational models had a very similar structure and the design reflected the structure of a multi-agent system: multiple agents act in an environment that represents the simulated 'world'. They each have a certain base knowledge, especially about processes, and perceive certain aspects of the world that are of importance for the simulated task. They use this information – which is not necessarily correct – to make decisions, and to act or communicate. Other agents can see their actions or 'hear' their communication and use this information together with their perception of the world to make decisions for actions.

Spatial and cognitive multi-agent simulations as described here are rather novel. Traffic models often use a multi-agent paradigm (for a list of projects see www.casa.ucl.ac.uk/agent.htm) but they typically do not contain models of cognitive aspects of human spatial behavior [20, 27]. Most examples of spatial simulations are based on cellular automata; agent-based simulations, which include cognitive aspects, do typically not include the spatial location and movement of the agents in space. The approach discussed here combines spatial and cognitive aspects.

In this paper we will introduce in the next section the concept of multi-agent theory and describe the particulars of the multi-agent systems we have built. Sections 3, 4, and 5 then review the models built to demonstrate to the reader what can be achieved with such methods. In Section 6 we generalize what we have learned from the three models built and in the concluding section we present areas of research in spatial theory where we expect to build computational models based on multi-agent systems.

2 Overview over Multi-agent Systems

Multi-agent theory is a young scientific field without common paradigms. Different people from different fields have different understandings about agents [3, 8, 19, 25, 28]. This section gives a short introduction to multi-agent theory and introduces the concepts and definitions we found applicable for our work.

2.1 Definition of a Multi-agent System

Adapting the definition of Ferber [8, p.11], the term 'multi-agent system' refers to a system consisting of the following parts:

- The *environment E* consisting of the following elements:
  - A set of *objects O*. Objects can be perceived, created, destroyed and modified by agents.
  - A set of *agents A*. Agents are a subset of objects ($A \subseteq O$) capable of performing actions - the active entities of the system.
  - A set of *locations L* determining the possible position of the objects (from the set *O*) in space.
- An assembly of *relations R* which link objects and also agents to each other.
- A set of *operations Op* enabling the possibility for agents to perceive, manipulate, create, destroy objects of *O*, in particular representing the agents' actions.
- A set of *operators U* with the task of representing the application of the operations from *Op* and the reactions of the world to this attempt of modification. The operators from *U* are called the *laws of the universe.*

2.2 What is an Agent?

According to the heterogeneity of the field there is no common agreement about a definition of the term agent. We regard an agent as *"anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors"* [25, p.31]. Agents are situated in some environment and capable of autonomous action [29]. Autonomy and the embedding into the environment are the two key properties of agents.

Our approach uses agents interacting in a multi-agent model as the basic concept for the description and representation of a domain. We use the term 'agent' as design model [13], i.e., we do not focus on the technical methods, e.g., on representation and reasoning mechanisms. The agent-based model will be expressed in a formal computational language. The language must be expressible and understandable enough to allow a sophisticated representation of the agent framework.

The agent should be able to act autonomously in its environment. Autonomous agents have control over their actions and internal state, i.e., the agent can act based on its own knowledge and perception. A system lacks autonomy if its behavior is completely determined by its built-in knowledge so that it does not need to perceive its environment to decide about its activities [25, p.35].

2.3 The Environment

Common to all environments is that they provide percepts to the agent and that the agent performs actions in them. Multi-agent theory regards the environment as an integral part of the framework. In general, two classes of environments can be distinguished: artificial and real environments [25, p.36]. Agents that are computer programs and exist in artificial software environments are called *software agents*.

The general rules governing the behavior of the environment are determined and represented by the laws of the universe U. In particular, the rules of the universe define the reaction of the environment to the actions of the agents.

Objects in the environment are located at some position in space (from the set of locations L). In the simplest case the environment consists of at least one agent in the set of objects O. The environment changes in time from one state to another. The reaction of the environment to the agent's actions changes the current world state.

2.4 Agent Architectures

The main criteria distinguishing architectures is the question of how much internal representation of the world the agents should have. Reactive systems have less or no internal representations, whereas systems constructed according to the deliberative approach have only symbolic representations. An agent constructed after the reactive approach purely reacts to its current percepts following condition-action rules. Deliberative architectures follow the classical AI approach (the Sense-Plan-Act paradigm [11]) that decomposes the control system of an agent into three elements: the sensing system, the planning system, and the execution system. The agent plans its actions based on its percepts and knowledge. The control flow between the three components is unidirectional from the sensor to the effector. The agent architecture presented in this subsection follows the Sense-Plan-Act paradigm.

The interaction between the agents and the environment defines the dynamics of the multi-agent system. This interaction is determined by the decision making process of the agent about the actions to perform (operations from the set *Op*) and the reaction of the environment to these actions (operations from the set *U*). The structure of the decision making process provides the foundation of the agent architecture. It can be divided into two components: the perception subprocess and the decision subprocess. An agent can be described by a function *perceive* and a function *decision*:

$$perceive: E \rightarrow P^*$$

The function *perceive* represents the perception process of the agent. It maps the environment to a set of percepts. The realization of the function *decision* representing the decision making process of the agent depends on the selected architecture. Agent architectures can be distinguished according to the implementation of the *decision* function. Here we distinguish two classes of agent architectures:

- reactive agents and
- agents with internal state

To allow higher-level internal capabilities of the agents, such as planning, goal directed behavior and collection of experiences, an internal representation of the world is necessary and not possible without internal state.

A purely reactive agent is characterized by the fact that it directly maps input to output, i.e., percepts to actions. The function *decision* of the reactive agent is a function of the following type:

$$decision: P^* \rightarrow A$$

It transforms a set of percepts P into an action A.

For agents with internal state the decision function has a more complex form. It includes the built-in knowledge, i.e., the former experiences of the agent, into the decision making process.

$$decision: P^* \times I \rightarrow A$$

The *decision* function maps a set of percepts and the current internal state I of the agent into an action A. The decision function consists of two steps. The first step (the function *updStateP*) updates the internal state of the agent based on its percepts; the second step (function *act*) selects an action based on the updated internal state.

$$updStateP: P^* \times I \rightarrow I$$
$$act: I \rightarrow A$$

The function *runEnv* represents the reaction of the environment to the agents' actions.

$$runEnv: E \times A^* \rightarrow E$$

It maps the environment E and a set of actions performed by the agents to a new state of the environment. This mapping function realizes the changes on objects (including agents) caused by the agents' actions; other changes in dynamic environments are also possible.

2.5 Cognitive, Spatial Multi-agent Systems

With our approach we construct software agents that act in artificial environments. These environments are intended to represent parts of the real world we are interested in, i.e., for the simulation of cognitive, spatial processes.

Mark et al. [16] present a hypothetical information flow model for spatial and geographical cognition, which consists of four stages: acquisition of geographical knowledge, mental representation of geographical knowledge, knowledge use, and communication of geographical information. Within our approach we focus on all four of them: the agents perceive their environments, form beliefs about the environment, use these beliefs to decide upon actions, and communicate with other agents. Agents with internal state are necessary to provide sufficient capabilities for the representation of cognitive processes. The function *decision* provides a general definition of cognitive processes describing these processes as a mapping from percepts and internal world representations of the agent (the internal state) to activities the agent performs in its environment.

An explicit representation of space is provided by the set of locations *L*. Agents can change the location of objects in space by their actions. The function *runEnv* represents reactions of the environment to the agents' modifications. It defines the general rules for change in the environment (the laws of the universe *U*). A cognitive spatial multi-agent system defines a qualitative notion of time represented by the change of the system from one world state to the next (i.e., a time discrete simulation). The transition is realized by the operation *runEnv*.

3 Example 1: Navigation in an Airport

Many people find it difficult to navigate through unfamiliar buildings because they are not provided with adequate wayfinding information such as obtained from signs. Agent-based simulation of wayfinding tasks helps to determine where people face wayfinding difficulties, why they face them, and how wayfinding information and environments have to be changed to avoid such difficulties.

In this research we are trying to find the minimum set of components an agent-based process model for wayfinding needs to include for simulating successful navigation. Furthermore, we are interested in the minimum amount of information, i.e., knowledge in the world, necessary for a cognizing agent to perform goal-based wayfinding tasks in an unfamiliar environment.

3.1 The Situation

Wayfinding in an airport represents a special case of moving through a building. Passengers at an airport have to find their way from check-in counters to gates, from gates to the baggage claim area, and between gates. They are often in a hurry and cannot afford to get lost. This can be a difficult task, because many airports are poorly designed, have poor signage, and are crowded. Also, many passengers are unfamiliar with the particular space and fast motion, which puts them in stressful situations. Things become even worse in emergency cases such as fire accidents. Making wayfinding easier for passengers at an airport requires designing airport space and providing wayfinding information (e.g., signs) in such a way that it facilitates people's execution of tasks.

3.2 The Computational Model

The wayfinding model (Figure 2) integrates the agent's cognitive schema and perceptual structures within a Sense-Plan-Act approach [11]. It focuses on external knowledge to explain actions of the agent performing wayfinding tasks. We use the concepts of *information* and *affordances* to describe the kinds of knowledge agents derive from the world by means of visual perception. Affordances [12] are possibilities for action with reference to the agent. Information (such as from signs) is necessary for the agent to decide upon which affordances to utilize. The environment provides percepts (i.e., affordances from cognizing agents and non-cognizing objects) to the agent; the agent decides upon and performs actions in the environment, which in turn provides new percepts; and so on. The internal cognitive schema [17] guides the agent's processes of perception, decision, and action during the wayfinding task. Information about the task and goal, and a minimum of wayfinding strategies and commonsense knowledge are necessary for the agent to perform the task. The task description directs visual perception in such a way that the agent samples only task-relevant information and affordances (therefore only a subset of all affordances present in the environment). The wayfinding model concentrates on the actual information needs during wayfinding and does not focus on learning a spatial environment. Its fundamental tenet is that all information must be presented at each decision point as "knowledge in the world" [18].

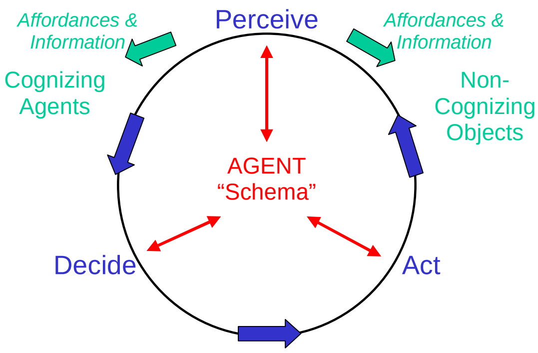

Fig. 2. Process model for wayfinding

3.3 Assessment of the Wayfinding Simulation

The formal specifications of the agent-based wayfinding simulation allow us to analyze the wayfinding process of an agent in an airport. Let us assume that the agent's task is to find its way from the check-in counter to a gate. We want to know if the agent is able to reach its goal based on the information and affordances offered at different viewpoints (i.e., knowledge in the world), and if not, where and why the agent faces wayfinding difficulties, and what can be done to avoid them.

If the agent has reached its goal, then the complete history of the agent gives information about all perceptions, decisions, and actions of the agent during the performance of the wayfinding task. If the agent gets stuck at a decision point, then the simulation halts and the missing piece of information is determined. Furthermore, it is possible that the agent is caught in a loop, in which case the decision point where the agent has been misinformed (e.g., a sign pointing in the wrong direction) is shown. Based on the results of the simulation the signage in the airport can be changed to facilitate the performance of wayfinding tasks.

As this is a simulation, it can be used for the assessment of airport designs before they are built and can be used any time the layout of paths in an airport is changed.

4 Example 2: Making and Using Maps

We discuss the simplest situation of map making and map use, applied to a city street network. The map produced should serve to assist people navigating in the city.

The research questions are: How to measure the quality of a map? How can the semantics of the map signs be defined?

4.1 The Situation

Surveyors explore the environment, measure position of points of interest and collect other information of interest. The information collected is then represented in a map, drawn to scale and with appropriate signs. Map users acquire a copy of a map, read it and use it to determine the shortest path to their destination.

A complex real situation is simplified in various directions: only the street intersections are of interest, users navigate between street intersections. At each street intersection, the points to which the roads lead are recognizable. The street network is finite (and small).

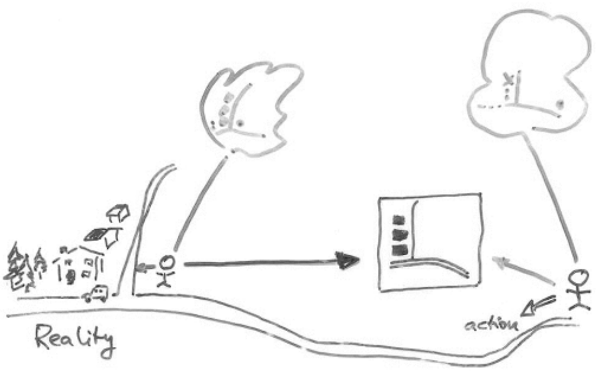

Fig. 3. An agent producing a map and another agent using the map for navigation

4.2 The Computational Model

There are two types of agents: surveyors and map users. The surveyor starts at an arbitrary street intersection and moves along the streets, taking note of which points are connected, until it has explored all connections. For each intersection point, the position is measured and the coordinates recorded – we assume here that surveyors carry some kind of GPS receiver and read coordinates off this device. It is important to notice that the knowledge the surveyors collect is not necessarily accurate and complete – the surveying equipment may be faulty, observations may be in error and the exploration may be incomplete. The surveyor agent's knowledge of the world is not a one-to-one copy of the description of the environment.

Once the environment is completely explored, the surveyor produces a map at some scale, which is represented as the list of commands necessary to draw a plotter: for each street segment, a line is drawn, and for each node, the label is positioned at the corresponding location. We excluded the translation of this 'abstract structure' of the map into a raster image of a map to avoid the difficult problem of raster interpretation in the map-using agent. For testing our assumption that this represents a map, we have constructed a very simple program, which takes such a simulated map and actually draws the corresponding image on a screen! Again, the map-making process is not necessarily a correct representation of the surveyor's knowledge and in consequence of the limitations of the surveyor's knowledge, not necessarily a correct representation of the environment.

A map user picks up a copy of the map, reads the lines and nodes of the map and builds a mental database of knowledge of the environment. Again, the map reading is not perfect and can introduce new errors into the representation the agent forms of the situation of the environment – adding further to the errors committed by the surveyor in exploring, measuring and mapping. Map users cannot measure coordinates, but they read the length of street segments of the map and use this for the determination of the shortest path.

The map user then makes a decision about the optimal path from its current location to its destination, using the knowledge acquired from the map (shortest path is selected for simplicity – other criteria for the path selection would be possible). The map user then moves according to its plan along the street network to its destination.

4.3 Assessment of Map Quality

In this simulation, the quality of the map produced can be assessed by observing the effectiveness of the movement of the map user: if the map is effective, it finds its destination on the shortest path; the longer the path it travels, compared to the actual shortest path, the less effective the map is.

The representation of the environment must not have commissions or omissions, which affect the calculation of the shortest path; the distances represented in the map must correspond to reality (close enough to not affect the decision on shortest path), etc. Each of the different errors that can occur from observing the environment, in the surveyor's mental representation, in the transformation to the map and from the map to the map user's mental representation can affect the effectiveness of the map communication. Each effect can be simulated separately or in conjunction with others in the model. We are currently using a similar model to gain a handle on the economic value of quality in a map [15].

4.4 Definition of Map Semantics

The semantics of the map signs are defined here as correspondence between reality and map representation – this is the conventional Tarski semantics. In this model the connection between environment (reality) and representation (map) is established from observation and map drawing completed with the connection between representation (map) and environment (reality) through the use of the information represented.

One can clearly see that the road classification the surveyor employs and the road classification of the map user must correspond. If the surveyor explores the street network with an (ordinary) car, then roads that are closed to car traffic will not be included. The resulting map is then less effective for a map user who travels on foot or using a bicycle. The semantics of the road classification is therefore grounded in the actual physical or legal classification of a road with respect to travel on foot, on a bicycle or with a car. This classification is 'reality tested' by surveyor and map user when they travel along a road segment.

5 Example 3: Property Registration to Secure Land Ownership

We discuss the structure of reality in a cadastre as part of social reality in general. We investigate the embedding of a cadastral system into its environment. The philosophical foundation of the analysis is Searle's theory of institutional reality [26]. He describes how the physical and social part of reality are linked and how institutional concepts are based on phenomena existing in physical reality.

The research questions we pose are the following: Is it possible to construct a computational model of (social) reality in a cadastre? Does Searle's theory give the appropriate theoretical framework for this task?

5.1 The Situation

The foundation for efficient cadastral systems is the understanding of the reality, which the system should correctly represent. It is not sufficient to investigate only the cadastral registry with its content and input and output operations. The registration process in the cadastral registry captures only a part of reality. The complexity of phenomena involved makes it necessary to widen the scope to the more general view of reality in a cadastre that comprises the cadastral registry as well as people acting in the real world. This allows representing a more comprehensive view of the cadastral domain. It allows the discussion of the information system cadastre embedded into its environment.

We regard reality in a cadastre as a part of social reality, which is highly determined by institutional concepts. Searle's theory gives the theoretical background to represent reality as consisting of physical phenomena and generally accepted institutional status assigned to physical phenomena (e.g., human beings and the status 'owner of a parcel' assigned). Rights and duties are assigned to status and determine the dynamics of the system. People act according to the rights and duties defined by the legal system. There are complex relationships between institutional concepts and physical phenomena. The institutional status defined by the legal system is always based on the physical situation in reality. For instance, the status 'owner of a parcel' is always linked to a physical foundation, i.e., a human being, a piece of land and the physical possibility to use the piece of land, which is the content of the ownership right.

5.2 The Computational Model

In the computational model the world is represented as consisting of agents and land pieces and a message history (the documentation). Agents communicate by exchanging messages. Agents have an internal state that comprises three elements. First the agent's internal state represents beliefs about the status assigned to objects (e.g., this piece of land is a parcel, this agent is the owner of a particular parcel). Second, the internal state of the agent represents the current goals the agent has (e.g., an agent can have the goal to sell a parcel.) The third element of the agent's internal state are the duties an agent currently has with respect to its own institutional status (e.g., the seller of a parcel has the duty to transfer ownership to the buyer by registering the transfer in the land ownership register).

The execution model of the agent-based model follows the architecture presented in Section 2. We distinguish the world level and the agent level of the execution model. On the agent level there are the activity functions of each agent representing the perception, decision, action cycle of the agents. The world level represents the reaction of the environment to the agent's activities (i.e., to the physical and communication actions of the agents).

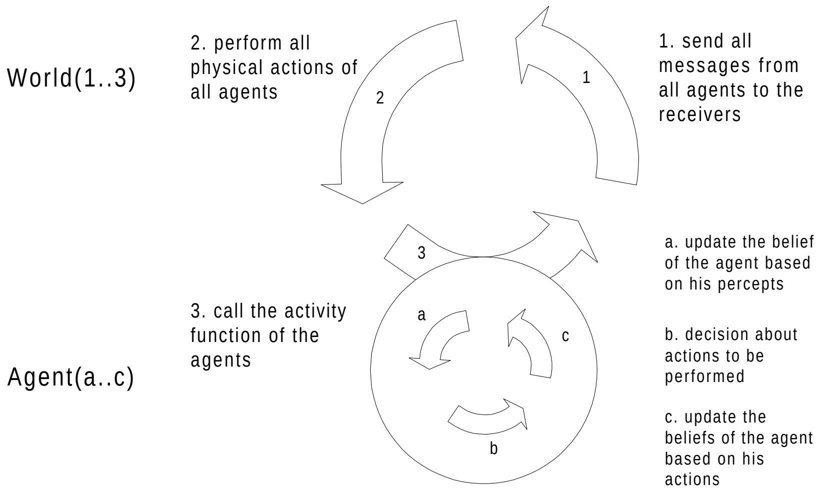

Fig. 4. The execution model

The simulation consists of two parts that are chosen as case studies for the validation of the model. The goal is to show typical cases of processes in reality of a cadastre.

First transfer of ownership on a parcel between two persons will be modeled. The computational model consists of three agents: the seller, the buyer and the registry agent representing the work of the cadastral registry. Buyer and seller conclude a sales contract. The seller applies for ownership transfer and the registry agent performs the transfer by registering the new owner in the land ownership register.

The second part of the simulation describes reality in a cadastre in the situation that conflicts between people occur in the case of unauthorized land use. It simulates a legal action and a judgment execution process. The simulation comprises four agents. One agent represents the legal owner of a parcel; one agent represents the unauthorized user of the land. Two other agents represent the court responsible for the complaint and the sheriff who has the physical power of the state to enforce judgments. The legal owner of a parcel recognizes that an unauthorized person uses his parcel (we use an abstract notion of land use, which is exclusive). He sues against the unauthorized user. The judge will pronounce a judgment creating the execution title for the legal owner of the parcel to apply for judgment execution. During the execution the sheriff will evict the unauthorized land use.

5.3 The Representation of Reality in a Cadastre

We have found that it is possible to construct a formal, computational model of a cadastre based on Searle's theory of institutional reality. This result has three aspects. First, Searle's theory allows computational model construction. Second, Searle's theory is sufficient and powerful enough to represent a complex part of reality, a cadastre. Third, the fact that we successfully constructed and validated the model allows the conclusion that a theory of the institutional part of social reality is sufficient to explain the structure of reality in a cadastre.

The extension of the scope from the cadastral registry to reality in a cadastre was helpful for the analysis of the cadastral domain. We were able to discuss a broader variety of issues, because change often occurs outside the scope of the registry but nevertheless with strong impact on the cadastral system.

It was necessary to model social reality in an agent-based framework. The model construction based on Searle's theory was only possible with an appropriate representation of human intentions and behavior. The agent-based model was the conceptual framework used for this purpose. We have shown the potential of agent-based models for the investigation of social reality.

With agent-based simulation we were able to validate the model with respect to the reality it represents. We developed a framework for the simulation of social processes of reality in the model and tested it by representing two nontrivial cases of processes from cadastral reality. This framework is extensible to represent more comprehensive parts of the legal system.

6 Common Structure of Cognitive Spatial Multi-agent Models

These models have in common that they model space, time and the cognition of the agents.

6.1 Space

The environment is spatial, which means that some basic properties of space and how objects exist in space are part of the 'laws of the universe':

1. Agents are located: each agent is located at a determined location and can only be located at one point at the same time.
2. Agents can move from point to point (i.e., we represent their moves in a discrete way and abstract from people's continuous movements in the real world); such moves must follow an established path and may be further restricted.
3. Land as a resource for use is part of the model; so far, land use is of a single type and exclusive, but more sophisticated land uses are possible.

These three points seem to cover the essence of space and spatial decisions: movement decisions require 1 and 2; location and allocation decisions are based on 3. This links to and advances into computational models work by Couclelis [4, 5].

6.2 Time

The models are implied temporally based on an algebraic approach: the fundamental operation is the advance of the model in time, which triggers all perception, communication, decision, and action to the environment. The model is essentially a function that constructs a new state of the environment from the current state (represented by the operation *runEnv*). It is possible to analyze sequences of states to understand temporal properties of the model. Explicit time can be introduced.

6.3 Cognizing Agents

The agents perceive the environment *E* and build a mental representation of what they have perceived (the internal state *I*). This mental representation is then used in the decision function. Both perception operation (function *perceive*) and decision operation (function *decision*) are designed to simulate limited aspects of corresponding human activities.

The simulation contains at the same time a computational model of reality (the environment *E*) and a computational model of the mental representation of this environment in the agent's mind (in multiple, different instantiations for each agent: the internal state *I*). These models are all different; the environment stands for the 'true reality' and the models the agents construct are 'their beliefs' (in the sense of [6]) upon which they act. The clear separation between reality and mental representation is a novel aspect of these computational models.

7 Implementation

The three examples have been realized using the functional programming language Haskell [21]. We selected simple, but typical aspects to develop the concepts and implemented them with an interest in clarity of expression. Performance using an interpreter was sufficient and we have not yet experimented with compiled versions. The code for all three examples is available from ftp://ftp.geoinfo.tuwien.ac.at.

The first example is 13 pages of code; the second example uses 12 pages of code (including the shortest path algorithm). The third example is somewhat larger and needs approximately 25 pages of code.

We decided not to use one of the available multi-agent languages and the corresponding run-time support. We wanted to reduce the amount of assumptions built in to a minimum and to be certain to understand all of them. We did not identify a multi-agent software environment specifically responding to our needs, and we were afraid that the amount of learning and adaptation would be larger than what was necessary to construct the multi-agent control structure.

In the near future we have the plan to integrate the three independently developed control structures into a single system and make the spatial aspects of the environment compatible. Most important is the effort to improve the structure of the agent's activities. We want to achieve a generalization, which can form the base to build more complex computational models.

8 Future Work

We have developed the multi-agent simulation with very simple models that helped us to identify the important parts and to isolate different aspects into separate classes (algebras, with operations and axioms). Using the same framework, more complex models are currently under way:

- A simulation to establish the influence of quality of a road map for navigation. The less quality a road map has, the more often the calculated shortest path cannot be followed to the end – due to an error in the data set – and an alternative route must be calculated. This is in all cases longer than the desired shortest path and will require more time, which can be translated into economic value.
- A simulation to integrate the guidance of travelers with the communication of the necessary information about business processes. This project addresses in particular the questions of users of a public transportation network, who must be informed about the departure location of trains, busses, etc., but must also be instructed about the 'business' requirements, i.e., acquiring a ticket, obtaining a reservation, etc.
- Extend the models to make it possible to obtain information about the time and cost of processes. We are interested to learn about the time an operation requires and how much it costs. For example, how long does it take to complete a transfer of ownership in a cadastre? How much cost occurs to the previous owner, the new owner, the registrar, etc.
- Simulations with multi-agent systems can help to explore how technical systems and legal requirements interact. We found that spatial, cognitive multi-agent systems could be used to simulate new technical systems and explore how humans can interact with the system, how safeguards could be circumvented, fraud possible, etc.

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