Decision Support Systems Based on Multi-agent Simulation for Spatial Design and Management of a Built Environment: The Case Study of Hospitals

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Abstract. Social dimension is a fundamental part of sustainable spatial planning, design and management. Envisioning its requirements and consequences is of the utmost importance when implementing solutions. Decision Support Systems aim towards improving decision-making processes in the development of infrastructures and services. They assist decision makers in assessing to what extent the designed places meet the requirements expressed by intended users. However, there is an intrinsic limit in the forecasting of emerging phenomena in spatial complex systems. This is because the use of built environment could differ from its function since it changes as a response to the context and it reflects emergent and dynamic human spatial and social behaviour. This paper proposes a Multi-Agent Simulation approach to support Decision-Making for the spatial design and management of complex systems in risk conditions. A virtual simulation shows a hospital ward in the case of health risk due to Hospital Acquired Infection, with an emphasis on the spatial spread of the risk. It is applied to find out correlations between human characteristics, behaviours and activities influenced by spatial design and distribution. The scenario-building mechanism is designed to improve decision-making by offering a consideration of the simulation outcomes. The visualization of how a building environment is used is suitable in verifying hypotheses and to support operational choices. The proposed framework aims at assessing and forecasting the building's capacity to support user activities and to ensure users safety.

Keywords: Decision support system · Multi-agent simulation · Human spatial behaviour · Hospital acquired infection · Spatial design

1   Introduction

In spatial design and management appropriate and rapid decision-making is a critical feature. Nevertheless, decision situations are often complex and multidisciplinary and usually involve multiple agents and types of information. Additionally, the structure and behaviour of a complex situation can raise uncertainty since these are neither well-structured nor clearly defined. As a result, more and more often there is no prescriptive or consistently valid process that can be followed to produce desired solutions.

Decision-making entails the analysis of a real-world system through methods and models and consideration of the context and its variables. The objective of the analysis aims to understand the system of interest and use this knowledge to facilitate decision-making. At the same time, the aim of decision-making influences the way in which decision support systems are designed Fig. 1. The objective of decision-making is to plan policies and measures that oversee and direct the development of the system. Decision-making involves identifying the various possibilities of alternative actions and choosing one or more of these through an evaluation process which should be sensible, rational and based on evidence [1].
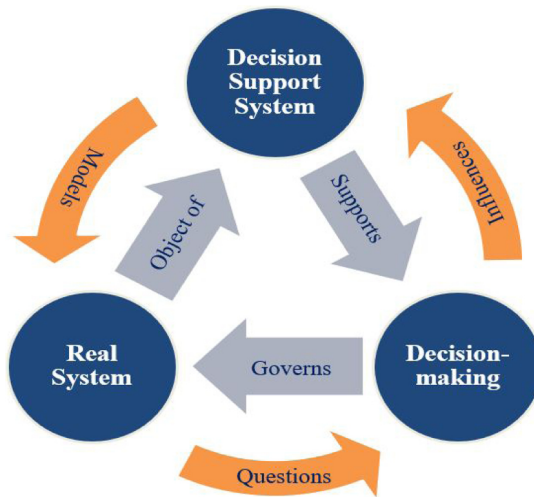

Fig. 1. Decision Support System relational framework.

Decision Support Systems (DSS) help in estimating the implications and consequences of possible decisions before their actual execution, allowing for better decisions [2]. DSSs are fundamental when a decision-making process requires the synthesis of a variety of information produced by multiple sources, when multiple possibilities of choice are involved and when, due to the wide variety of potential outcomes, it is important to justify the decision that is made.

Indeed, DSSs are designed and implemented to address complex decision situations, where it is beyond the capability of individuals to understand and reprocess all

the necessary information to significantly describe them. In such cases, distributed data must be collected and organized to support problem analysis. Advanced computer-based tools, such as Multi-Agent simulations, are used to provide a framework for people to explore a problem, learn about it and use the knowledge gained to arrive at conscious decisions. An effective Multi-Agent simulation is a simplified replica of a real-world system which has reached a convenient trade-off between realism and usefulness. DSSs based on Multi-Agent simulations help describe the evolution of the system and its constraints, provide knowledge-based formulation of possible decisions, simulate scenarios of consequences of actions and assist in the formulation of implementation strategies. This decision-making process is often iterative since alternative actions are analysed and information gained from the what-if scenario analysis is used to guide it further.

Decision-making in land engineering, urban planning and architectural design have long-term implications which directly affect the Built Environment, consisting of a network of buildings, infrastructures, open spaces, and its users. They involve the realization of projects and public spaces to develop activities in selected areas. This in turn affects people's experience of cities and life, since built environments support the living and safety needs of their inhabitants. Research in the field of DSS applied to spatial planning and design aims towards improving decision-making processes in public administrations and aiding professionals in the field of infrastructural and service development within cities. Contemporary sustainable planning and design consider social dimensions as a fundamental part of it. Planners, architects and civil engineers should be able to assess to what extent the designed places meet the requirements expressed by their intended users. This is a task inherently oriented to consider human expectations, needs and behaviours. To date, they rarely find formal methods to forecast whether, from a user's perspective, the designed infrastructure will perform before it has been built and tested through use, especially for the most qualitative aspects, such as human satisfaction, productivity, comfort and safety. There is an intrinsic limit to what extent decision makers can use their imagination and experience to forecast emerging phenomena in spatial complex systems. This is because the use of built environment could be different from what the expert may realize, since it could differ from its function. The use changes as a response to the context (cultural, environmental, psychological, and more). It reflects emergent human spatial and social behaviour, and because of this it is more dynamic than functional, e.g. it can change from person to person and in a short time.

However, even if human related aspects are too complex to be predicted accurately and a gap exists between expected and actual behaviour, decisions cannot simply be ignored. In spatial design and management, envisioning the various consequences of implementing specific solutions is of the utmost importance for the decision to succeed [3]. Decision makers constantly search for innovative methods to assess the implications of decisions related to humans in space, as these are crucial in addressing design issues appropriately and as early and thoroughly as possible. Likewise, in everyday hospital life, safety and health risks arise and must be managed through decision-making processes. Here a virtual simulation of a trial case study shows a healthcare system under conditions of risk, with the aim of forecasting and assessing the building's capacity to support user activities and to satisfy users' safety needs. Thus, it is

used to illustrate the potential of a Multi-Agent simulation approach to support decisions. All decision-making processes start from the recognition of a problem, and then from its definition to the solution. Specifically, our issue is that of healthcare environment design and management in the case of the health risk due to Hospital Acquired Infection (HAI), i.e. infections contracted during hospitalization, with emphasis on the spatial spread of the risk [4].

2   Background

Practitioners and policymakers usually rely on (and at the same time respect) regulations, design rules and legislative factors. Even though they have at their disposal several computational tools to evaluate quantitative building performances and characteristics such as costs, energy consumption, material features, structural stability and so on [5], analytical approaches in evaluating most qualitative aspects suffer from severe limitations and neither can a real-size prototype be built and tested before construction itself. Therefore, their capacity to fully comprehend the complexity of human-building interaction (e.g. building-use, human spatial behaviour, human satisfaction and safety issues) has shown its limits, mirroring the increasing complexity of building design and variety of human behaviour with all its consequent requirements [6]. Such a real-world system is too complex to be evaluated through analytical solutions, which are not available or are computationally inefficient [7]. Alternatively, it could be replicated and therefore studied by means of computer simulation. A simulation model is preferable to modelling complex systems as it is more appropriate for modelling dynamic and transient effects [8]. It appears to be the best choice for investigating Human Spatial Behaviour. A realistic simulation of a built environment with a Multi-Agent System (MAS) emulates either the behaviour of a single person or collective actions, accounting for how humans act and interact with each other and with the environment [9, 10].

A MAS is defined as a set of agents operating and interacting simultaneously in a shared environment, under different initial conditions and constraints [11]. MAS agents show the ability to solve problems at individual level and to interact in order to reach global objectives. The interaction may take place between agents as well as between agents and their environment. In MAS, the researcher defines the behaviour of the single agent at individual level and the system behaviour emerges from multiple local interactions between them. This leads to a dynamic and unpredictable evolution of the system, which is thus referred to as complex. Multi-Agent Simulation has been recognized by international literature as an efficient method for evaluating the performance of designed systems when the relationships among decision variables are too difficult to be established analytically [12]. To this end, virtual simulation is a valuable approach in investigating "what-if" scenarios. It offers the potential to identify new understanding of how a built environment may operate, providing evidence in support of decision-making processes [13–15].

Recently, following the Multi-Agent paradigm, the Event-Based Modelling and Simulation (EBMS) approach has emerged to address these issues. Developed by Schaumann et al., it is based on the Event notion. Events are designed to coordinate

temporal, goal oriented routine activities performed by agents. Rather than describing behaviour from the point of view of each actor, events allow for the description of behaviour from the point of view of the procedures that need to be performed to achieve a task [16]. The event system architecture adds the capacity to manage the coordinated behaviour of multiple agents in a top down fashion to the bottom up structure of the ABM. Its power to simulate complex and realistic scenarios with a flexible user interface allows us to apply it to the simulation of Human Spatial Behaviour in a Built Environment. Such a Multi-Agent Simulation approach incorporates a number of factors such as a description of actors' organizational roles and hierarchies, activities involving more than one actor and adaptability in response to dynamic changes in activity priorities, unplanned events, or non-typical circumstances, such as when an actor is not available to perform a task when expected.

3   Methodology

HAIs are infections caused by microorganisms acquired within a health care facility by a patient who was admitted for a reason other than infection [4]. A prevalence survey conducted under the auspices of the World Health Organisation (WHO) in 55 hospitals of 14 countries representing 4 WHO Regions (Europe, Eastern Mediterranean, South-East Asia and Western Pacific) showed an average of 8.7% of hospital patients who had nosocomial infections [17]. HAIs are a significant burden both for the patient and for public health resources, since treatment is very costly and may not be effective. What is more, organisms causing HAIs can be transmitted to the community through discharged patients, Healthcare Workers (HCW) and visitors, which may cause significant disease in the community.

The contamination propagation phenomenon has multi-factor roots and proceeds through a dynamic transmission mechanism which often leads to outbreaks. It overlaps hospital processes, events and workflows. It is restricted through infection prevention and control procedures and it influences and is influenced by spatial design and distribution. Literature confirms that the conventional ways that hospitals are designed contributes to danger [18]. It shows that the physical environment strongly impacts on hospital acquired infection rates by affecting both airborne and contact transmission routes. Ulrich's research identified more than 120 studies linking infection to the healthcare built environment [19]. A critical challenge for architects is to improve the physical setting design to make hospitals safer, with improved healing procedures and better places to work by reducing risk from HAIs. Nevertheless, guidelines for the design of healthcare facilities are often vague in their formulation [20]. Thus, there is an urgent need for a DSS method which demonstrates how a better hospital ward spatial design could contribute to HAI prevention and control and to support decision makers with choices that could impact on the safety of users.

We propose an event-based decision-support system for hospital design and management, which can be applied to predict, prevent, and manage health risk due to Hospital Acquired Infection (HAI). The model enables the simulation and coordination of multiple actors' behaviours, which affect (and are affected by) the dynamic spatial and social context. The aim is to reveal the mutual interactions between a built

environment and the behaviour of its occupants to inform a buildings' design or renovation. In the event-based model, the decision-making authority is stored in Event entities, which direct the collaborative behaviour of a group of actors to perform an activity in a given space. Events afford top-down coordination of actors' scheduled behaviour (e.g. a doctor's patient check round) while accounting for bottom-up adaptations to spatial and social contingencies (e.g., impromptu social interactions between a doctor and a patient), which can delay the performing of scheduled activities. Each event includes a set of (a) *preconditions*, which specify the requirements for an event to be triggered, (b) *performing procedures*, which guide the event's execution, and (c) *postconditions*, which update the state of the entities involved in the event's execution. Events meaningfully combine 3 different components to describe context-dependent behaviour patterns, namely *spaces*, *actors* and *activities*. To reduce events' computational efforts in managing the performing of behaviour patterns, each of the constituents, are endowed with autonomous calculation abilities. Results of such calculations can be communicated to the event to assist its decision-making process. *Spaces* contain geometric and semantic information and can automatically modify their status depending on the actors they host and the activities performed. *Actors* are associated with specific roles in the building organization, knowledge about the space and other actors, and a dynamic status that records the current space where the actor is located, the activity performed, and other additional metrics for evaluation (e.g. the walked distances). *Activities* direct the low-level interactions between actors and their environment. To model human behaviour patterns at increasing levels of complexity, events can be aggregated into tree-like structures, called narratives. A narrative manager coordinates the performing of human behaviour scenarios composed of planned and unplanned narratives. Planned narratives are performed at a specific time, while unplanned narratives emerge in response to social, spatial and environmental conditions.

In the virtual simulation, the behaviour of agents and their conditions and contamination capacity is formulated using a discrete equation formulation. Further details on the weighting of various parameter and their interaction in the system, i.e. likelihood of certain behaviours or events can be found in Esposito [21]. The transmission model and equation were then implemented within the Unity 3D environment where the spatial semantics, actors' profiles, activities, events and the contamination model were coded in C#. This allows for the understanding of the phenomena directly through an infection risk map visualization, which reveals how social interaction and spatial influences affect the spread of HAIs.

4   Case Study Simulation

Decision making is considerably difficult when the objects of interest are complex infrastructures such as hospitals, where performances are related to several functional, typological and organizational requirements. It is also where, among other factors, human considerations such as satisfaction with the quality of care and patient and staff safety are major concerns.

Indeed, human related sciences such as architecture and urban planning tend to work formulating context-dependent methods and developing knowledge models to support and improve the decision-making processes in a specific domain and case [22]. Nevertheless, case study research excels at providing an understanding and explanation of a complex issue and can extend knowledge, add strength or disprove theories [23]. Case study evaluation emphasizes detailed contextual analysis of specific events or conditions and their relationships. Therefore, the case study approach is especially well-suited to produce the kind of knowledge required to support the decision-making process [24]. Indeed, it is useful for both generating and testing hypotheses in carefully planned and crafted researches of real-life situations, issues and problems. The testing of hypotheses through case studies relates directly to the issue of case selection. The strategic choice of case in relation to the research objectives may greatly add to the generalizability of a case study [25].

With this rationale, the proposed simulation illustrates the applications of the EBMS approach to the healthcare environment domain. The simulation displays a building use situation where simulated actors (doctors, nurses, patients, visitors, etc.) perform tasks according to pre-planned schedules (medicine distribution, patient check, patient visiting, etc.), while dynamically responding to social encounters and environmental conditions. In addition, they respond to un-planned events (e.g., "code blue" when a patient is in cardiac distress), and act accordingly. The hypothetical scenario scene shows an HCW workflow interruption situation. To build up a reliable simulation, an observation and analysis of human behaviour in built environments was adopted, based on the POE paradigm. Data was collected on user activities with direct-experience observations, shadowing, tracking people and interviewing medical and administrative staff, patients and visitors. Moreover, references, guidelines and sessions with experienced medical practitioners led us to understand the features of HAIs and the established protocols and best practices to manage them. Further details on this process are provided in Esposito [26]. This phase helped us to accurately represent the complex inter-relations between all the major features involved in the case study narrative, which unfolds as follows: HCWs start from their staff station before moving to the central medicine room to prepare medicines. Afterwards, they move through the patients' rooms to distribute these. During the simulation, a random number of visitors enters the ward to meet their relatives, each one visiting a single patient. They walk through the hallway to reach the patient's room, where a social interaction takes place for a certain amount of time. Afterwards, visitors leave the ward from the same entrance. In the simulation, emergent events could be triggered when specific spatial and social conditions arise. It may occur that when a visitor encounters a HCW, the close proximity between the two drives the visitor to interrupt the HCW scheduled duties to start a social interaction, e.g. visitor asking information about his family member condition, before the HCW returns to his planned activities, as does the visitor. The proposed scene starts with a visitor leaving his relative's room when an actor enters the room to attend to the other patient. This situation forces him to wait in the corridor and then unexpectedly interrupt the HCW workflow while he is performing a round of visits. The visitor who has been in direct contact with his infected relative (making him a carrier), in turn contaminates the HCW. In this situation, the HCW fails to observe Hand Hygiene protocol, therefore he spreads contamination to subsequent

patients during the round. In the meanwhile, the space populated by these contaminated actors also becomes contaminated Fig. 2.

The case study reveals the narrative nature of the HAI spread phenomenon, which is well represented through the EBM simulation narrative approach. Moreover, it allows for the visualization of the risk of contamination propagation due to human spatial behaviour and user activities in the built environment, through real-time results displayed with changing colours for actors and spaces, ranging from green to blue for higher contamination risk.

The simulation presented is not focused on predicting the future accurately; instead, our approach is diagnostic, i.e. it is used to understand and explore the MAS model which has been exploited to describe the system [27]. The capacity of the simulation to account for both situations when a clear sequence of observable factors and planned activities can be recognized and when emerging unplanned behaviour complicates situations, demonstrates the capacity of the simulation system to account for changes that are not obvious. The working proof of the "what-if" scenario allows for an understanding of the possible state patterns in the development of the contamination propagation. Moreover, this proves its value as a DSS in the field of hospital management of infection risk, e.g. when employed as a forecasting tool for the evaluation of policies and also on the process of design of hospitals.

In fact, a system user can test the potential risk of different real-life situations by simulating new scenarios with new input conditions and with system parameter tuning, e.g. actors' profiles and behaviour and re-configuration of settings. Although in the simulation the duration of the activities was reduced to condense several hours of activity into a few minutes, the type of each activity and the duration of each contact can be easily modified in the user interface. Likewise, the number of non-colonized, colonized and infected actors can be adjusted to reflect the desired proportion. It is possible to run a scenario in which a percentage of total patients have a predisposition to the acquisition and development of infection, as in the case of the presence of immunocompromised patients or caused by virulent pathogens. Finally, since there can be uncertainty concerning the primary source of transmission, in certain circumstances, HCWs are the cause for transferring bacteria to patients, whereas in others, this could be due to visitors or the environment. If a study into how infection propagates from the flora of a health care environment is required, as in the case of epidemic exogenous environmental infections, it is straightforward at the beginning of the simulation to set a scenario whereby the initial cause of infection spread resides in a contaminated space, adjusting the starting contamination level for the selected spaces.

5   Conclusions

The present study proposes a Multi-Agent simulation functioning as a DSS for hospital management and design, providing evidence in support of underlying decision-making processes. The focus of the paper is on the development and use of a MAS simulation to support decision-making. Indeed, in cases of multiple complexity, its core capability is based on gathering, structuring and presenting knowledge. This involves dealing with the so-called wicked problems for which the decisional approach aims to address

Fig. 2. Contamination risk map for people and spaces.

problems structuring rather than solving them. Furthermore, it means reaching a decision which is satisfactory rather than optimal, avoiding the risk of unintended consequences.

To demonstrate the usability of the proposed approach a virtual scenario is reported. The simulation illustrates the potential applications of the proposed MAS approach through proof-of-concept case studies. The proposed case study interprets the overall course of human spatial behaviour, starting from human states and contextual conditions and ending with activities set in space, allowing for the real-time visualization of contamination transmission under the effect of breaks in prevention measures. It visualizes the pathogen propagation, correlating with the architectural ward layout and workflow organization in a case study of HCW workflow interruption. The scenario-building mechanism is designed to improve decision-making by offering a consideration of the simulation outcomes and their implications. Indeed, the development of the system is fundamental in verifying hypothesis and to support choices. Specifically, this process provides the following features:

- to test "what-if" scenarios in order to explore the effects of possible design solutions for the HAI phenomenon and to define a balanced, satisfactory trade-off with building requirements;
- to estimate the effectiveness of a range of policies aimed at preventing and control the HAI spread and to represent the impact of social and spatial factors on the performance of procedures dealing with the outbreak;
- to evaluate to what extent the EBMS framework can be applied for modelling and simulation of complex human spatial behaviour to support decisions and management for spatial design of a built environment.

The elaboration of the research study can lead to the broader purpose of improving understanding of the potential impact of physical and social settings in a built environment on users. Moreover, it provides insights about human spatial decision-making and actions to help policy makers and experts to interpret the relationship between the organization of places and spatial behaviours. Therefore, the scope of the current research is:

- to provide a visualization of how a building is used and experienced;
- to forecast and assess the building's capacity to support user activities and to satisfy users' functional needs, e.g. safety and satisfaction;
- to examine how well the virtual simulation of human behaviour can be suitable in estimating human-related building performances;
- to support designers while making decisions that could impact on the lives of the users of future buildings;
- to evaluate alternative building project proposals and designers' choices before moving onto the construction phase.

The Multi-Agent simulation is applied to find out correlations between human characteristics, behaviours and activities in case of HAI risk, which give us hints on the role of the space design. Indeed, the principal value of the research is to build a framework to improve the planning and design of a human-cantered built environment, thus enabling a consideration of the use of built infrastructures by user agents.

Providing visualizations of how a building is used in a design phase has the potential of envisioning the various consequences of implementing specific design solutions. Accordingly, an understanding of individual decisions in actions and behavioural processes in space can support professional knowledge and public administrations in their decision-making procedures in the field of urban infrastructures.

A new scenario is to be developed which compares two slightly different spatial configurations, while maintaining all the other fixed variables and conditions. This further experimentation is designed to exploit analysis into whether the architectural layout alone affects, by fostering or hindering, HAI propagation, e.g. understanding how different ward designs can lead to different dynamics of infection diffusion.

The results analysis might enable the evaluation of how an intended design meets infection control and prevention requirements. This application will support the design team and hospital managers in the evaluation of functional design solutions connected with safety requirements, suggesting potential improvements.

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