In-Process Agent Simulation for Early Stages of Hospital Planning

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Abstract. In the early stages of hospital planning, work processes are typically modelled in a static manner, using flow-charts or business process modelling notation as means. Diagrams of this kind are easily simulated, however, employed process engines lack possibilities for dealing with dynamic aspects of the process which depend on the building layout (e.g. elevators, behaviour of automatic delivery carts). If one could give planners the opportunity to employ dynamic entities without having to change their usual workflow, one of the benefits would be that they are not being forced to resort to naive assumptions (e.g. 15 seconds per floor) that are still commonplace in today's planning practice.

Introduction

Hospitals, like airports and some types of industrial facilities (e.g. oil platforms), are process-driven buildings: Their design depends foremost on the planned work processes that enable them to operate day and night, 365 days a year. Therefore, the process model of such a building constrains the architectural design, which must evolve in close cooperation between process planners and architects.

Because processes are modelled in highly-formalized manner (e.g. as flow-charts), one might think that the application of simulation lies at hand from the very start of a building project.

However, such *static* process descriptions lack the ability to also include aspects that *depend on the building layout*, such as the transition of persons and material from one space to the other, possibly using *dynamic* entities such as lifts as they move along. Resorting to naive assumptions (e.g. fixed passage times) might be inadequate (again taking the lift as example) and, furthermore, cumbersome to elaborate: In early planning, there are usually *several variants* of the spatial concept rather than only one for later phases.

Our work therefore focuses on overcoming the mentioned problems, by embedding dynamic entities into an otherwise static process model. Broken down into further detail, our contribution consists of:

- A thorough look at simulation needs in the early stages of process-driven building design (see 'Background', Section 2). Such a survey is (surprisingly) novel, as the community has previously targeted hospital simulation problems but not their context within the planning process.
- An extension of *static* process simulation such that *dynamic* entities (acting in a *spatial context*) can be represented. Technically, this is achieved by invoking an agent-based simulation on behalf of the process simulation (see An Early Stage Hybrid Simulation, Section 3).

As side-note and constraint, we want to augment the now-common working style of planners in a non-intrusive manner, i.e. extending rather than reinventing design tools available. The choice of an agent-based simulation *on top of* a process simulation fits exactly this line of reasoning.

1 Related work

Business Process Simulation (BPS) is based on linking a graph-based model to a *Discrete Event Simulation* (DES) that simulates its behaviour over time. There exists a variety of software packages implementing BPS (e.g. Rücker 2008, Dodds 2005), plus some DES packages that provide a 'flow-chart' like approach by means of a server/client based model (Sadowski and Bapat 2001, Nordgren 2001, Nordgren 2003, Concannon et al. 2003).

When it comes to simulation that requires an understanding of the spatial concept (as in the previously mentioned examples of elevators and automated delivery carts), we see that most of the DES seem to focus on late design phases, i.e. phases in which the spatial concept is already fixed and subject to optimization (e.g. via Laguna and Martí 2003). Especially in hospital planning, this might be a problem, since spatial design is subordinate to the process model, and might thus not be evolved as far as the latter when a simulation is performed. We have, therefore, previously presented a coupled pedestrian/process simulation targeted at early design stages, in which the early concept (also called schema) is taken into account (Wurzer 2010). Our efforts for this paper are approaching the problem from a different side: Our goal is to enable planners using a static modelling approach (i.e. flow-charts) to include dynamic entities into their process descriptions, based on a BPS being linked to a Agent-Based Simulation (ABS). We are aware of many approaching being occupied with this specific hybrid approach (e.g. Remondino 2003, Borshchev and Filippov 2003). However, none is focused on the planning context of early-stage hospital design, which is essential when producing an approach that is adapted to working routines now in place.

2 Background

The simulation needs for early-phase hospital design are closely connected to the design process. In the following subsections, we will describe the typical planning tracks and deliverables in early design, before coming to the actual problem areas in which simulation can provide valuable input when being used as a design tool. Because of space constraints, we have omitted a discussion on the influence of different design methods used, and may forward readers interested in this topics to (Jones 1992, Lawson 2005).

2.1 The Early Design Process

There are two design tracks that are important to early-phase hospital design: *Building Organization* and *Functional Planning*.

Building Organization. (see left part in Figure 1) is occupied with the planning of the organization from the side of business administration, i.e. definition of the organizational structures (departments, sub-departments), work processes and responsibilities within these. In essence, the planning work proceeds top-down: Starting with a very coarse outline of business activities required for operation (Figure 1a), a basic formulation of processes can be derived by introducing temporal and causal order (Figure 1b). The notation of these processes depends on preferences of the project team, two usual options are flow-charts or process graphs according to the recently standardized Business Process Modelling Notation (BPMN).

As the project progresses, some activities might need to be further detailed in order to be fully defined. This can be done by using sub-processes, which establishes a hierarchy of activities within activities (Figure 1c). Furthermore, when detailing a process, responsibilities for each activity are also assigned to different collaborating departments within the organization (see Figure 1d). The finished product and goal of the building organization is thus a description of the whole operation of the building from a business side (also called 'process model' of the organization). The process model acts as input and constraint for the functional planning track.

Functional Planning. (see right part in Figure 1) starts with a definition of building functions (i.e. capabilities of a building, see Figure 1e), based on the intended vision (laid out e.g. in the tender document, project description etc.) and process model of the organization. These functions are then correlated in a adjacency matrix (White 1986) by the degree of collaboration, ranging from 'adjacent' for closely collaborating areas to 'dislocated' for areas that do not cooperate or must be separated e.g. because of hygienic considerations (Figure 1f). Adjacent functions are then grouped into spaces (refer to Figure 1g): In the example given, 'operation theatre' and 'recovery' are put into one common space (signified by a dashed border), while 'trauma' stays isolated and gets its own space. The so-found spaces are then arranged in a preliminary floor plan called 'schema' (see Figure 1h), with each space being represented by a rectangle.

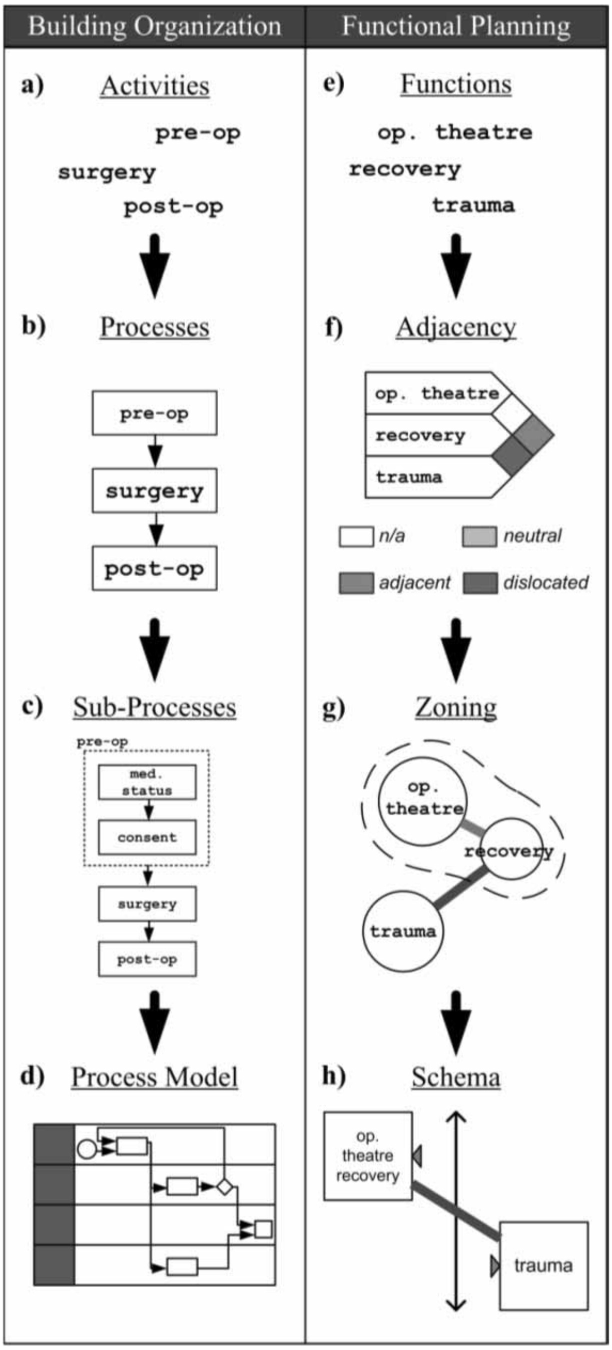

Figure 1: Early-stage planning tracks. (left) Building Organization: (a) Activities formed into (b) processes and (c) sub-processes. Furthermore, assignment of process responsibilities to different departments leads to (d) process model, which acts as input and constraint for (right) Functional Planning: (e) Functions are (f) related via an adjacency matrix, (g) grouped to form (h) spaces within the architectural schema. Circulation is additionally inscribed using arrows.

In this context, the rectangular form of every space is not to be taken literally, since it merely gives the proportion, approximate size and location in relation to other spaces. The concrete form for each space is beyond the work done in early-stage design - it occurs later, in a phase called 'Form Finding'. Apart from the spaces, the schema also contains arrows that give the preliminary circulation system (e.g. corridors) of the building. Aside from the graphical notation, the schema is typically also given as spreadsheet form ('Space Allocation Plan'), which listing spaces (often grouped by function), cardinality (e.g. $2x$) and usable area per space (e.g. $25m^2$), commonly regulated by guidelines and planning handbooks such as (Neufert 2000). Depending on project structure, the Space Allocation Plan may be produced during Functional Planning or be given before the actual planning work starts, as an input (e.g. when extending a building).

It is noteworthy that the activities of *Building Organization* and *Functional Planning* are not sequential but inherently parallel: As process model and the spatial concept are detailed and evolve side-by-side, the planning team has to ensure consistency of both models (Wurzer, 2010). Furthermore, the spatial concept might fork of a variety of alternative designs, which must then later be reduced or merged by design decisions (i.e. documented argumentation within the planning team leading to a set of choices, see Kunz and Rittel 1970, Rittel and Webber 1984). For process-based buildings in the early planning stages, these design decisions are typically based on:

Urban Context. The relation between the planned building as a whole (i.e. arrangement of spaces and circulation) with its surrounding environment and existing infrastructure (White, 1983). For example, traffic patterns resulting from local public transport and motorized individual traffic have to be taken as a constraint. Visibility of landmarks has to be preserved by (and likely used in) the proposed design.

Adjacency. Short paths between collaborating units (defined by the adjacency matrix), considering the adjacency matrix (White 1986), process model and expected volume of building users requiring service. Vice versa, a separation of spaces for reasons of privacy (e.g. secure areas vs. public spaces, inpatient vs. outpatient areas) and for sustaining building operation (typically by service corridors, allowing for repairs and delivery 'behind the scenes').

Separation of traffic. Different routing according to type of traffic (Lohfert 2005), e.g. separation of staff from visitors and patients, low-priority from high-priority traffic (e.g. emergencies), building users with appointment from the ones without, soiled from clean material, etc.

Location, size and proportion. Placement of spaces is not isolated from considerations of the building as a whole; for example, certain areas of work favour natural lighting (e.g. patient rooms, energy considerations for the whole building), while others can do without. Proportion and size of individual spaces determines the opportunity of future adaptations (e.g. change in equipment), while at the same time being subject to optimization (minimal area needed per function, compactness).

Orientation and wayfinding. Depending on intended user spectrum, orientation can play a vital role for the whole building project. The transition of building users from one space to the other must be considered both in terms of the process as well as existing previous knowledge about the building layout. Spaces serving processes used by temporary building users must be easy to reach (i.e. no signage required) and memorize (e.g. using a main corridor connecting all departments) . A clear readability of space can also help in fire safety and evacuation planning, conducted in later phases (Illera et al. 2008).

Extensibility and adaptability. Both extensibility and accessibility of a building is given by the configuration of spaces and circulation (Neufert 2000) - the first one deals with openness to the outer environment, the second with (usually multi-functional) hub spaces that serve as distribution points for pedestrian traffic, often located at prominent positions within the building. The ability to adapt the spatial concept to future requirements of the process also requires an evaluation from a multi-functional view (e.g. interdisciplinary use of a space, shared workspaces, etc.).

Adequacy of planned concept. The adequacy of both spatial concept and process model is an overall judgement of the building's design under consideration of the planning task. Argumentation focuses on whether the design satisfies the vision and financial context stated by the client. In the planning team, the discussion is centred around the types of functions present and sizes of their respective spaces as well as structure of the processes and needed resources.

2.2 Early-stage simulation needs for hospitals

Given the mentioned design decisions in early planning phases of process-based buildings, simulation can contribute tools for assessing a variety of parameters which can then be weighted according to the planning objectives (i.e. multi-objective analysis). Statements produced in this manner are necessarily qualitative, since spatial concept and process model are in a preliminary stage:

Visibility, accessibility and wayfinding. The analysis of these parameters may be done statically (for the whole building, its arrangement of spaces and circulation network) or dynamically (by simulating individual processes). In the first case, reachability analysis of the circulation network can be conducted for both interior and exterior space by using the methods provided by Space Syntax (Hillier and Hanson 1984, Hillier 1996), which can also compute the visibility from each point in the building (e.g. for hiding areas for supply and disposal). Viewshed computations, usually found in Geographical Information Systems (GIS), can be used for the same purpose. Wayfinding, on the other hand, requires a dynamic simulation of individuals following their processes (e.g. using ABM). In this connection, algorithms from pedestrian dynamics may be used to simulate the physical movement under the influence of congestion (e.g. using Helbing and Molnár 1995).

Space placement and dimensioning. Previously defined adjacency relations can be verified by simulating the planned processes by means of BPS, ABS or system dynamics (SD). The volumes of traffic between the spaces, distances travelled over the circulation and simulated times taken must correlate with the relationships given in the adjacency matrix. Furthermore, the dimensioning of spaces can be checked by considering the volume of persons present in each time step: In the simplest case, the occupation is related directly to the presence of persons in a space (e.g. in entrance areas). Moreover, presence in a space may relate to waiting for a shared function (e.g. examination), which can be modelled as server with a specified number of resources (e.g. 2 doctors) and one or more queues. By correlating the observed size of queues with the space requirements for waiting areas (distinguished e.g. for sitting and lying patients), it is possible to attain a hint at minimal areas required.

Norms and regulations further contribute to these space requirements, which could be checked using approaches from automated building code checking (Eastman 2009), albeit in a simplified form. A further opportunity for comparing the placement of spaces is that of building physics simulation: Some workplaces might require daylight; others must be protected from it. Preliminary environmental simulation (light, shadowing, wind), can also hint at energy demands which are elaborated in later phases.

Movement, circulation and traffic. Different options of route choice can be simulated by either assigning waypoints between subsequent activities of the process explicitly (e.g. delivery of goods in zigzag shape, one floor at a time) or by interpreting the circulative network as graph on which shortest paths are computed. As a matter of fact, spatial arrangements can be judged by the time it takes to move across the circulation (which is also depending on the processes in place). A separation of traffic can further be achieved by attributing the circulation with allowed types of traffic (e.g. patients, visitors, staff), and taking these into account during either automatic or manual route planning. A further attribution of the circulation arrows has to be performed for distinguishing between horizontal traffic (taking place in the same level) and vertical circulation (lifts and stairs), among which movement models and speeds might differ.

Usage. Functions give the purpose (or intent) of spaces, processes model their planned usage over time. By coupling activities of the process to the underlying functions, a static check for unused function or activities that have no reference to a function (i.e. the underlying spatial concept) can be made (Wurzer, 2010). Furthermore, temporal usage of functions obtained via process simulation can be used to compare the prominence of the spaces containing them and help think of possibilities for multi-functional use: Areas that are used only part-time (e.g. lunch room) may be conveniently used for other functions (e.g. meeting room) during the rest of the day.

3 An Early-stage Hybrid Simulation

The problems and design decisions presented under Section 2.1 demand, above all, a solution with reference to the spatial concept (Section 2.2), in which dynamic aspects such as wayfinding, movement etc. play a role.

This is a dilemma, since the process modelling approach commonly used is inherently abstract, i.e. non-spatial. In order to make dynamic spatial simulation within a static BPS possible, we have extended a commonly used process modelling platform (Microsoft Visio) for which a multitude of process simulation add-ons exists (e.g. ProModel Process Simulator, Simul8 and Arena Integration).

Our implementation follows the seemingly usual approach for adding simulation capabilities to Visio, by writing (1.) a script in Visual Basic for Applications (VBA) that (2.) exports the flowchart in a custom format and (3.) calls upon an external program to do the actual process simulation. In order to avoid licensing issues when making our work available, we have opted to use the open-source BPS implementation provided by (Baeyens 2005) instead of a commercial engine. Furthermore, (4.) we have employed NetLogo (Wilensky 1999) as ABS platform, which is also available under open-source license terms.

3.1 Calling an agent simulation from inside a process

Our central point of intervention lies in the introduction of a new type of activity in the process diagram that was coined as *agent node* (see Figure 2a). This new node type acts as an injection point for dynamic behaviour inside the static process.

An agent node is a proxy for an agent simulation that is executed on behalf of the BPS. Upon entering an agent node, the process execution is passivated and control is passed to an ABS, which performs a spatial simulation as required by the planning process; in the simplest case (which we have implemented) the route of an agent from one space to another is computed. In order to be able to call the ABS, an agent node holds parameters specific to its model (e.g. 'from' and 'to', Figure 2b). Generally, there will be several agent-based models running in parallel to the BPS, each one covering a different aspect of dynamic behaviour needed (refer to Section 1.2). As a matter of fact, every model will have its own type of agent node holding required parameters. Under the hood, the different agent models are implemented as servers listening on distinct ports (see Figure 2c showing the mapping of agent models to ports), communicating bidirectional with the BPS.

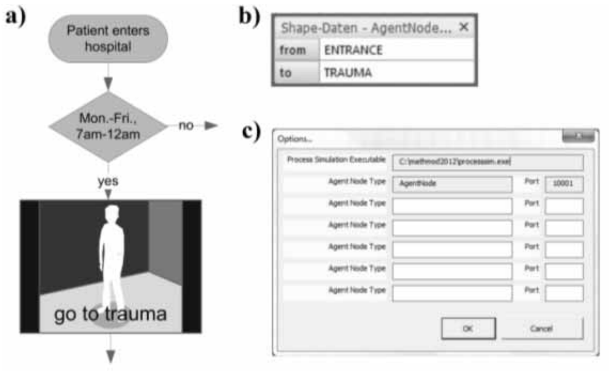

Figure 2: (a) An agent node being embedded into a static process. (b) Properties of an agent node. (c) Options dialog showing the connection settings, which let Visio communicate with process simulations and agent models.

3.2 Synchronization between process and agent simulation

As previously mentioned, a process execution that reaches an agent node is passivated for as long as the called agent-based model runs. However, because BPS and ABS typically differ in their time bases (future event list versus simulation in seconds), some synchronization construct is required.

In simplest approach (which we have undertaken), BPS and ABS both progress in seconds. For each time step, (1.) the BPS executes processes scheduled at that instance. Then, it (2.) issues the command to begin simulating that time-step to all ABS, which (3.) perform computation and (4.) report the list of agents that have completed their task in this time-step back to the BPS. (5.) The BPS waits for all ABS to finish computation, then (6.) reactivates process executions that have waited for the completion of an agent model.

A more elegant but also more complex way for synchronization would be to only simulate in time steps when needed (i.e. when ABS are active), and employ discrete scheduling based on the future event list in all other cases. We clearly see this as a future work item and optimization task for our approach.

3.3 Agent-based simulation

ABS simulations are occupied with simulating the dynamic aspects of the process depending on the building layout. The implementation we used computes the passage from one named space into another, taking into account the circulation and existence of lifts, which have their own behaviour (see Figure 3). On startup of NetLogo, the program opens its receiving communication port. Upon (1.) receiving the request to simulate a time-step, which may also contain the command to insert a new agent into the simulation, the simulation (2.) advances all agents and (3.) compiles a list of those that have finished their task, which it (4.) returns to process simulation. The wayfinding algorithm used is based on previous work, as given in (Wurzer, 2010). Furthermore, the agent-based models contains multiple variants of the spatial concept, which can be used to compare different spatial options. In our simulation, the spatial concept is chosen when starting the process simulation. The underlying data is hardcoded for the time being, in a full-blown implementation, this could be loaded from a Computer Aided Design (CAD) file or any other form of database containing the schema. Another way for obtaining the schema, which we find is preferable, is to use the agent model directly as a design tool (i.e. develop the schema directly inside the model) - thus embedding simulation fully into the design process.

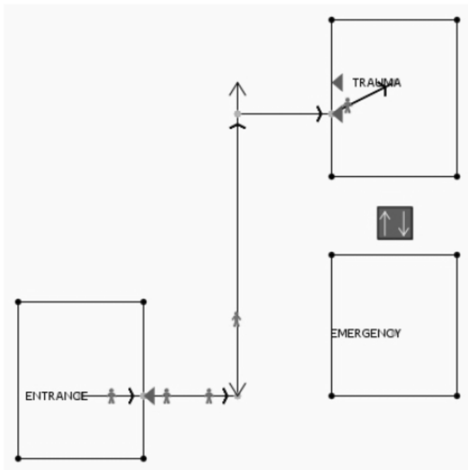

Figure 3: Agent-based NetLogo simulation for computing the passage between named spaces, taking the circulation (middle line with arrows) into account. Also simulates an elevator to the ward, which has its own behaviour.

3.4 Connectivity between implementations

An overview of the connectivity between the different applications written is shown in Figure 4: Visio uses the embedded VBA scripting engine to first output a file containing the process definition, then opens the process simulation app as well as all agent simulations. From then on, the communication proceeds solely between the process simulation and the agent simulations, bidirectional via sockets.

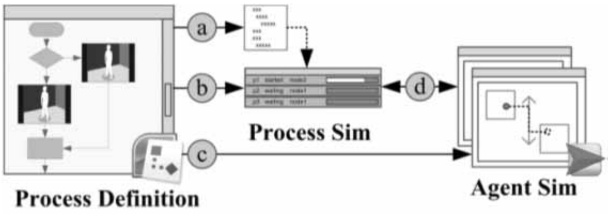

Figure 4: Implementation. (left) Processes drawn in Visio are (a) written to a file, which is fed into a (b) process simulation that can execute them. Visio furthermore (c) opens all agent simulations for the process model, which are (d) then invoked by the process simulation.

We have presented a simulation approach by which dynamic entities can be embedded into an otherwise static process. Our efforts are targeted at early stages of hospital planning, where simulation has the potential to become a design tool for qualitative decisions among a multitude of design variants. Our implementation (which is being made available under the website www.iemar.tuwien.ac.at/processviz/early-stage-sim), consists of an extension to Visio flowcharts in the form of a custom 'agent node' that invokes a process simulation communicating with an agent-based simulation. As outcome, we are able compare different spatial configurations with regard to how long it takes to cross different areas of a hospital being planned. However, our approach offers many more opportunities for being used in today's planning practice, as outlined under Section 1.2. Therefore, we see the technical part of our contribution only as minor outcome of the paper, the real impact lies in the possibility to shift simulation from late stages of design (where possibilities of change are limited), to early stages, where design decisions are of fundamental significance.

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References

[1] Baeyens T. JBPM: Graph Oriented Programming [Internet]. [cited 2005] Available from: docs.jboss.org/jbpm/v3/userguide.

[2] Borshchev A, Filippov A. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. In: *Proceedings of the 22nd International Conference of the System Dynamics Society;* 2003.

[3] Concannon KH, Hunter KI, Tremble JM. (2003). Simul8-Planner simulation-based planning and scheduling. In: *Proceedings of the 2003 Winter Simulation Conference*; 2003. P. 1488-1493

[4] De Vries B, Jessurun AJ, and Dijkstra J. Conformance Checking by Capturing and Simulating Human Behaviour in the Built Environment. In: *Proceedings of Sixth Design and Decision Support Systems in Architecture and Urban Planning*; 2002. P. 378-391

[5] Dodds S, Designing improved healthcare processes using discrete event simulation, *British Journal of Healthcare Computing and Information Management*. 2005; 22(5): 14-16.

[6] Eastman C, Lee J, Jeong Y, Lee J. Automatic rule-based checking of building designs. In: *Automation in Construction*. 2009; 18: 1011-1033.

[7] Helbing D, Molnár P. Social force model for pedestrian dynamics. *Physical Review E 51*. 1995; 5: 4282–4286.

[8] Hillier B, Hanson J. *The Social Logic of Space*. Cambridge University Press; 1984.

[9] Hillier B. *Space is the Machine: A Configurational Theory of Architecture*. Cambridge University Press; 1996.

[10] Illera C, Fink M, Kath K, Waldau N, Rosic A, Wurzer G. NO_PANIC. Escape and Panic in Buildings. In: Proceedings of the fourth international conference on Pedestrian and Evacuation Dynamics; 2008. P. 733-742

[11] Jones JC, *Design Methods*. Wiley & Sons, London; 1992.

[12] Kunz W, Rittel H. Issues as elements of information systems, In: *Working Paper 131, Center for Urban and Regional Development,* University of California, Berkley; 1970.

[13] Laguna M, Martí R. The OptQuest Callable Library. *Operations Research/Computer Science Interfaces Series*. 2003; 18: 193-218

[14] Lawson B. *How Designers Think, The Design Process Demystified*. Architectural Press, Oxford; 2005.

[15] Lohfert P. *Methodik der Krankenhausplanung*. Lohfert & Lohfert AS, Copenhagen; 2005.

[16] Neufert E. *Architect's data*. Blackwell Science, Malden; 2000.

[17] Nordgren WB. Taylor Enterprise Dynamics. In: *Proceedings of the 2001 Winter Simulation Conference;* 2001. P. 269-271

[18] Nordgren WB. Flexible simulation (Flexsim) software: Flexsim simulation environment. In: *Proceedings of the 2003 Winter Simulation Conference;* 2003. P. 197-200

[19] Remondino M. Agent Based Process Simulation and Metaphors Based Approach. In: *Proceedings of the 4th Workshop on Agent-Based Simulation*; 2003. P. 93-97

[20] Rittel H, Webber M. Dilemmas in a General Theory of Planning. *Policy Sciences*. 1984; 4: 155–169

[21] Rücker B. *Building an open source Business Process Simulation tool with JBoss jBPM* [Master Thesis]. Stuttgart, University of Applied Science; 2008.

[22] Sadowski D, Bapat V. The Arena Product Family: Enterprise modeling solutions. In: *Proceedings of the 2001 Winter Simulation Conference*; 2001. P. 159-166

[23] White E. *Site Analysis: Diagramming information for architectural design*. Architectural Media, Tucson; 1983.

[24] White E. *Space adjacency analysis: Diagramming information for architectural design*. Architectural Media, Tucson; 1986.

[25] Wilensky U. *Netlogo* [Internet].c1999. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, Illinois. Available from: http://ccl.northwestern.edu/netlogo

[26] Wurzer G. Schematic Systems - Constraining Functions Through Processes (and Vice Versa). *International Journal of Architectural Computing*. 2010; 8(2): 201-217