Meeting Simulation Needs of Early-Stage Design Through Agent-Based Simulation

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Abstract. *During early-stage planning, numerous design decisions are taken in an argumentative manner, based on occupation with the building site according to the different influencing aspects (e.g. topology, wind, visibility, circulation, activities etc.). In this context, sketches, diagrams and spreadsheets are the workhorses for elaboration. However, some of these phenomena are dynamic by nature, and are rather poorly modeled when utilizing static media. In our work, we thus show how agent-based simulation can be used to compute and visualize dynamic factors, in order to inform the decision process on a qualitative level. As a matter of fact, simulations may be used as a design tool in their own right, for analysis and objectified comparison among multiple design variations.*
Keywords. *Agent-Based Simulation; Early-Stage Planning; NetLogo; Design Process.*

INTRODUCTION

In architecture and urbanism, problems have always been multifaceted and designers have tried to address them syncretistically. For example, each aspect of a design problem (e.g. site, circulation, client operation, costs) brings in a specific view and often wants to determine the design solution. Therefore, care has to be taken to balance and weight argumentation, both of which are hard to do when considering a problem of sufficient complexity. Agent-based simulation can contribute methods that help in this context; however, it remains underutilized in the early stages of architectural conception. To elaborate how and in which areas agent simulation can meet the decision needs during early-stage planning is therefore the main focus of this paper.

BACKGROUND

During the design process, multiple stakeholders from different disciplines have to take design decisions among multiple alternative (and likely competing) solutions. Like Rittel (1984), we are specifically interested in the argumentation behind such choices. We focus on early stages of architectural conception, which include site analysis (White 2004), functional programming and production of schemata (White 1986). In this context, Agent-based Simulation (ABS) can evaluate or generate a set of solutions according to the planning aspects being considered, by transforming them into a simplified model that uses the following concepts:

- **Agents**: The active entities within the simulated world.
- **Space**: The environment that agents act in. According to the simulation used, this may either be discrete (i.e. split into cells) or continuous, two- or three-dimensional.

- **Time**: Represents change acting iteratively on agents and environment, computed in discrete intervals (e.g. seconds, minutes or abstract 'ticks' of a simulation clock).

ABS has been extensively employed in related disciplines over the last 25 years or so. In urban modeling and geography, for example, ABS have been used to build simulations of traffic and pedestrian systems, crowd dynamics, land use and land cover change, urban population dynamics, residential location dynamics and urban growth, to name just a few. Urban planners and geographers are usually interested in examining current spatial configurations or predicting futures of existing cities and, therefore, their simulations rely on heavy GIS, demographic, and economic data inputs and complicated rule sets. Batty (2005), for example, sees cities as canonical examples of complex systems that are suitable for simulation: emergent, far from equilibrium, displaying high levels of entropy, irregular patterns of growth and decay at variable time steps. "In terms of many systems that exist in the real world," he asserts, "the only kind of experimentation that is possible is through computer simulation" (Batty, 2007). Research indeed shows that ABS are often better suited to study emergent irregular patterns, when compared to classical pattern formation models that rely on deterministic equations because they are more easily amenable to experimental observations (Bonabeau, 1997). It has also been argued that agent-based models are of relevance to the "design of distributed problem-solving devices, when finding the solution to a particular problem amounts (or can be shown to be equivalent) to forming a specific pattern" (Bonabeau, 1997). For design, the notion of experimentation is extended to predict forms of the system under future conditions that do not yet and may never exist.

An abstract view on the planning problem can help establish its essential properties at a very early stage. In this context, Coates and Derix (2007) speak of *syntactic* and *semantic models*: Syntactic models deal with spatial and configurationally concerns. Graph theory and other techniques are employed in order to establish abstract categories of organizations of space. Semantic models, on other hand, approach spatial configurations in terms of meaning. These meanings are of social, environmental, or programmatic quality - for example 'commercial', 'residential', 'proximity to stream' and 'sunny' or 'shady'. Joyce, Tabak, Sharma and Williams (2010) furthermore highlight the *multi-scale applicability* of ABS for early stage planning, and stress that it should be regarded not only as analysis tool but also as design driver in its own right.

CONTRIBUTION OF THIS PAPER

It is obvious that a coherent taxonomy of ABS in the early stages of design is infeasible, if not impossible. Therefore, while taking into account the current corpus of knowledge as presented in the background, we follow a more pragmatic approach for evaluating potential applications of ABS:

1. We identify decision aspects (see Fig.1a) in early-stage architectural conception that are poorly met by static media and may benefit from a dynamic visualization/simulation approach (see "*Simulation Needs in Early-Stage Planning*").
2. We describe *how ABS* can be used to meet the mentioned simulation needs (Fig. 1b), based on our own work in the preparation of an „architecture model suite", which we describe as we move along (see "*Agent-based Simulation as a Design Tool*").

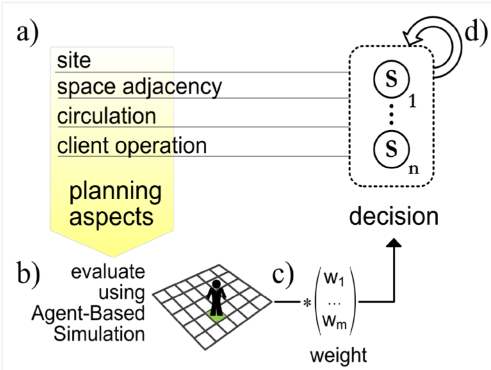


Figure 1
(a) Planning aspects that influence design decisions are (b) evaluated using Agent-based Simulation among a set of proposed solutions. The results are then (c) weighted, in order to arrive at qualitative statements that are tailored to the planning task. This decision process (d) is often iterated during early-stage planning, and influences subsequent simulation runs.

3. We take a step back and discuss the presented applications of ABS in the larger context of early-stage design decision processes (see „*Discussion*“ as well as Figs. 1c, 1d).

SIMULATION NEEDS IN EARLY-STAGE PLANNING

Early-stage design solutions are generated and evaluated in a multi-objective parameter space, in which each planning aspect offers a different view on the problem. Typically, such a view is presented (digitally or on paper) as a map, sketch, diagram or calculation - i.e. in a *static* and *deterministic* manner. We argue that *dynamic aspects* such as wind, noise, functional usage etc. are poorly captured using this approach, which regards objects (things) in space as primary and time and change as secondary. In the following section, we therefore identify some of these aspects worth simulating, highlighting these in **bold**. Our scope within the early design process is given by (White 2004, White 1986): From urban context to site planning, functional programming, schema and preliminary design.

Dynamic aspects concerning urban context and site planning

- *Climate* is determined by the interplay between **temperature**, **humidity**, **wind** and **rain temporally and spatially. Together with** *solar radiation***, these factors can form the basis of preliminary thoughts on sustainable building design.**
- *Location* **of a site** within a landscape or urban environment is given as a spot on a map. However, this does not account for **travel times**, which depend (1.) on the transportation infrastructure, the circulation and the volume of traffic using it and (2.) on the functional relations at that scale (travel will take place only to a limited number of other locations).
- *Natural physical features* (e.g. elevation, soil type, bearing capacity, vegetation) are derived by Geographical Information System (GIS) data. However, certain aspects such as **drainage patterns** and **water levels** are dynamic, and may require simulation.
- *Man-made features* (e.g. [built/open] spaces, roads) within and adjacent to the site define **visibility** (view into, from and through the site) for both the present state as well as a potential future use (as defined by zoning and future development plan). Built form is also vital for calculating the change in **shadowing** patterns.
- *Neighborhood context* (i.e. areas directly surrounding the building site) establishes possible sources for **noise** and **pollution**. Major features (natural or man-made) located adjacent to the building site also define visibility axes that need to be preserved during Site Planning. Apart from physical aspects, analysis might also deal with the **social context** (e.g. demography, crime rate, etc.), which is also a factor that absolutely cries out for modeling and simulation.
- *Circulation* (i.e. vehicular and pedestrian **movement**) is dynamic in multiple senses: Apart from the obvious fact that traffic volume varies over time and space, it is possible to also model the individual participants and their **route choice** (static route choice for visiting function sequences, adaptive route choice according to behaviour model and situation - e.g. shopping, wayfinding, egress situation, etc.).

Dynamic aspects concerning functional programming, schema and preliminary design

- *Client operation*, i.e. **usage of functions** in a specified **temporal and spatial sequence** is dynamic by nature. There are two different viewpoints in this context: One may look at the activities performed by (the different types of) **building users,** or at the spaces which serve as functional containers and are being frequented by the former (i.e. **space occupancy or level of service [Fruin 1971]**). As flow between functional areas is changeable over time, so are the resulting **functional relationships** (i.e. this can be compared to the adjacency relations that are specified in a static manner).

- *Location, dimension and orientation* of the building spaces with regard to the **sun path** are vital for ensuring natural lighting. Incident **solar radiation** can furthermore be used to consider energy efficiency at an early stage (also taking into account **shadowing**). Other aspects that apply at site level, such as **air flow**, **acoustics** and **view** (into, from and through the building) could in principle also be taken as decision aspects, however, as these factors depend already on form and choice of materials, an analysis might be more appropriate in later stages.

AGENT-BASED SIMULATION AS A DESIGN TOOL

In ABS, objects are viewed as secondary to the formulation of principles and processes through which things evolve and change. Simulation "seeks to formulate principles of architecture in this space of processes allowing space and time (architecture) as we know it to emerge only at a secondary level" (Testa et al. 2001). The emphasis is on understanding and exploring individual behaviours of design elements and their mutual influence on other elements. This viewpoint also encompasses recognition of hierarchies or levels (Wilensky and Resnick 1998) and understanding how complex, collective, macroscopic patterns emerge from entirely local and simple interactions of individual units.

To showcase how ABS can be used to cover the dynamic aspects presented earlier, we have developed an extensive "architecture model suite" for the freely available NetLogo ABS platform (Wilensky 1999), which we will describe in due course. The suite itself is being made freely available, with full source (see [1]).

Setting up the cell space

Before an ABS can be performed, the space in which the agents act must be initialized. For many of our simulations, this simply means that the cell space has to be cleared. However, some more elaborate models require the existence of specific types of spatial data:

- **Landscape Data.** Environmental information as provided by modern GIS can be imported into the cell space (see Fig. 2a). Both raster data (consisting of a grid of values) and vector data (consisting of points, lines, or polygons) are supported. Another possibility is the automatic generation of the landscape using fractals (e.g. midpoint displacement algorithm [Mandelbrot 1988]), for cases where reference to the environment is not meant literally. Generating landscapes has an additional benefit: as it is derived from fractal geometry, it reflects the overall shape in each of its parts. This property can in turn be used to see whether simulation results are similar across different scales (and if so, one can estimate the results of the model on a fine scale by running it on a coarser scale).
- **Schemata.** We offer the possibility to import preliminary sketches (see Fig. 2b) containing early-stage schemata with circulation depicted as axis-aligned lines and spaces as axis-aligned rectangles. The individual shapes are extracted in a two-pass algorithm: First, we use a connected-component labeling algorithm to extract clusters of pixels belonging to one shape. This is then fed into a feature extraction algorithm (based on the idea of the Hugh transform) that converts these pixel clusters into lines (circulation axes) and rectangles (spaces). As another possibility, we also offer an automatic schema generator (see Fig. 2c). A third possibility in the form of a schema editor (see Fig. 2d) can be used for digital sketching as well attributing imported sketches with additional information (e.g. for functions, since we are not trying to recognize handwriting from the sketches).

Early-stage simulation of dynamic aspects

ABS can either happen per planning aspect (i.e. many simulations running separately) or in the form

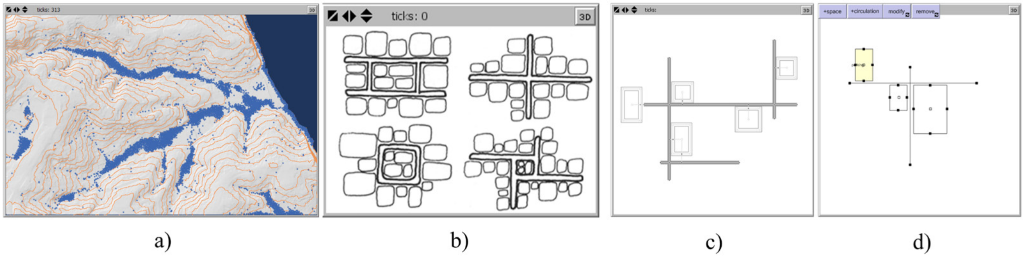
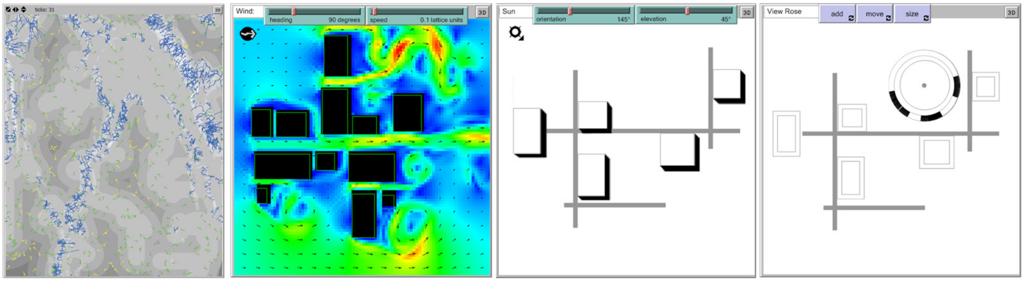


Figure 2
Setting up. (a) Landscape Data (b) Sketch importer for hand-drawn sketches (c) sketch generator and (d) sketch editor.

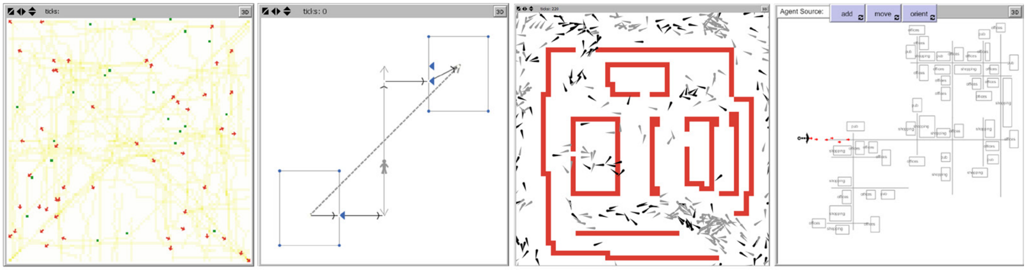
of one model covering multiple aspects at once. The risk of the latter approach lies in possible interference, which is why we have chosen to keep them separate:

- **Topography, Drainage, Water levels.** Our work in topographic simulation (see Fig. 2a) calculates surface drainage by dropping agents („rain") randomly onto the cell space, then letting them follow paths downwards into valleys. This example stands for a wider variety of models to take slope and elevation into account (e.g. water level computation or agents flocking along gradient, see Fig. 3a); additional entities acting as obstacles for the flow (barriers, dams) are given as interactive tools.
- **Wind, Pollution, Noise, Acoustics**. Simulation of wind flow in and around the building site, based on early-stage specification of spaces and pre-existing built environment, can act as a tool for a quick assessment of wind pressure and undesired turbulences. In our work, we use a Lattice-Boltzmann cellular automaton (see Fig. 3b) for performing necessary calculation Computational Fluid Dynamics (CFD) calculations, given the wind direction as parameter. Likewise, this model can also be adapted for the simulation of pollution propagation. The simulation of noise and acoustics is another extension of this method, although on a very basic level that does not fully take reflection, absorption, interference and other wave properties into account (lacking data in early stages).
- **Shadowing, Visibility**. Topography and site data (i.e. spaces attributed with zoning or building heights) can be used to calculate shadowing (see Fig. 3c). Agents are used as to cast rays in the sun direction, leaving shadows. The process can be iterated to show the dynamic change during a day. Visibility can also be computed by ray-casting. In principle, one might think that aspect would not be dynamic; however, there might be cases of occlusions that are time-based (e.g. tree foliage, draw bridges, docked ships) - in which this becomes useful. Generally (refer to Fig. 3d), there are two distinct measures of visibility, one „from" and one „to" a point of interest. Another method are dynamic visibility polygons (i.e. isovists), as given in (Turner et al. 2001).
- **Movement.** The simulation of pedestrians has been the predominant and most naturalistic use of ABS. For our work (see Fig. 4a), we have employed the movement model by Blue and Adler (2000), which is a lane-based model originally aimed at vehicular traffic simulations. We have extended this model for use also as a pedestrian model, by giving it 360 degrees freedom rather than being lane-aligned. The implemented model also records spatial occupancy (i.e. densities) and way-lengths per agent. For traffic that is strictly regulated (i.e. either users following fixed processes or vehicular traffic.), flow along a network-based model (e.g. as in Tabak 2008, Tabak et al. 2010) may fit better. Fig. 4b shows such a model for computing the minimal path along such a circulative network, which computes entry and exits points into-, and shortest path over the circulation (static route choice, dynamic simu-



a) b) c) d)

Figure 3
Spatial Aspects. (a) Agents interacting with topography or (b) as vectors of a wind field, (c) agents cast as rays to produce shadows and (d) perform visibility computations.



a) b) c) d)

Figure 4
Pedestrian aspects. (a) Pedestrian dynamics and space occupancy, (b) flow along circulative network, (c) group formation (d) function usage.

lation). The addition of behavioural rules, e.g. for shopping activities or egress, can be added at a higher layer, as in (Dijkstra et al. 2011). Another interesting feature is the group formation found in crowds (see Fig. 4c), as given by (Reynolds 1987).

- **Functions and Activities**. Agents as entities that perform activities in functional spaces have previously been researched e.g. in (Wurzer 2010). Our demonstration model (see Fig. 4d) selects, for every agent, a target space according to functions it intends to visit. The resulting passage along the circulative network is the same as before. Further methods of network analysis (e.g. reachability according to space syntax[2], functional relationships from agent flow [Wurzer et al. 2010]) are also included in our architectural suite, but not shown here.
- **Spread.** Agents can be used for generative processes as well, as shown in the City generation example in Fig. 5a and b: The progression of agents along a circulation being built up, leaving spaces as they go along, can be interesting from a process point of view (i.e. the generation itself is the design aspect). The sketch generator presented in Fig. 2b is also an example of such a process.

DISCUSSION

Evaluating a set of proposed design solutions via ABS (Fig. 1b) enables a comparison that can inform the decision process. As mentioned, simulation can either happen per planning aspect (i.e. many ABS running separately) or as one model covering multiple aspects at once. Albeit outcomes from simulation seem to be quantitative, they are not to be misunderstood as hard data: The reason for this is that they are derived from preliminary (and thus fuzzy) input, and are thus also fuzzy on the output side. What is needed is an interpretative post-step, in which the obtained values are given meaning.

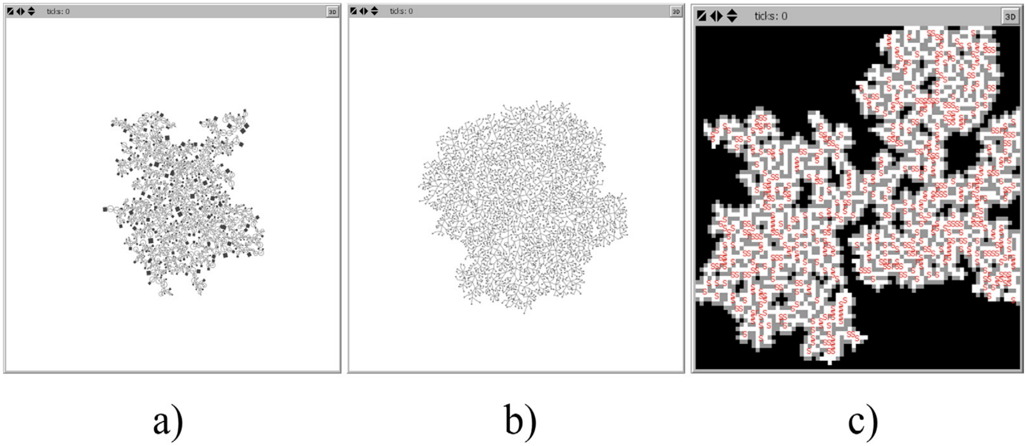


Figure 5
Modeling Spread. (a,b) Generative urban modeling, (c) spread of functional spaces.

For example, way lengths computed are in abstract 'cell space units'; they can be compared relatively, however, a better way would be to map them to an scale that is applicable (e.g. building scale) and then think about implications for the simulated group of persons (e.g. too long, long, medium, short). As the evaluated planning aspects are not equally important, they must be weighted (Fig. 1c) before the decision process takes place. This weighting lies outside the simulation, as it represents the discussion during decision-taking (Fig. 1d).

Among the modeling and simulation community, an often-discussed topic is also that of scale of the simulation model (i.e. microscopic, mesoscopic and macroscopic), which should ideally only be microscopic. Our choice is a more pragmatic one: As long the model is agent-based (and agents are: the animated parts of the world, each cell, all nodes and edges of a circulative network), we are happy to consider it. We are well aware, however, that in strict terms some models (e.g. the Lattice-Boltzmann CFD) are at least mesoscopic. A similar argumentation is also heard for model scope: An agent-based model should constrain itself to the minimal implementation needed to describe an effect. However, as we consider ABS as design tool, some additional steps such as the data import from sketches are necessary, in order to be able to work within the design workflow in place. Improved support for the import of sketches (e.g. more shapes in the schema, according to [Achten, Bax and Oxman 1996]) are definitively a future work item in this respect.

SUMMARY

We have argued for the introduction of Agent-Based Simulation (ABS) into the early-stage planning process, in order to be able to capture and evaluate design aspects that are inherently dynamic (e.g. wind, pedestrian flow, functional usage). One of the main advantages of this approach is that it makes it possible to experiment *on simulations of the real thing*, not on the real thing itself. Such computer models are essential planning instruments that make it possible to ask multiple 'what if?' questions about the system of interest. Our work and contribution in this respect is that we are transferring simulation concepts *into early phases of architectural design*, so that these questions can be asked earlier and thus with more influence on the rest of the design process.

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