Generating Urban Forms from Ontologies

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# Generating Urban Morphologies from Ontologies

Luca Caneparo*, Mattia Collo*, Davide Di Giannantonio**, Vincenzo Lombardo**,
Alfonso Montuori*, Stefano Pensa*
* High Quality Laboratory - Territorial Integrated Project, Politecnico di Torino
** Department of Computer Science, Università di Torino

**Abstract**. The paper presents the ongoing research work on a software system for supporting the exploration of the numerous and often interrelated factors that can affect the urban design.
The present implementation of the system supports the simulation of different urban scenarios in relation to the uniqueness and constraints peculiar to a design and a site.
The paper considers our ongoing research work to formally represent the implicit and explicit knowledge used by means of ontologies. The ontology semantic system administrates a set of rules and relations among urban entities. To this aim, we are dealing with different issues: all the factors involved in the urban design process cross various domain knowledge, from different competencies and sources; the knowledge is both semantic and procedural.

**Keywords**: urban ontology, generative systems, multi-agent model.

## 1. Introduction to urban design

Numerous and often interrelated factors potentially concur to urban design (Alexander, 1996). The number of these factors is recognized large, furthermore they are often ill-defined, and can assume different meanings relating to the urban and cultural context. They often play in interrelated ways: "depending on how it is acted upon by other factors and how it reacts to them" (Jacobs, 1961). Jane Jacobs also stated: «Cities happen to be problems in organized complexity, like the life sciences. They present "situations in which a half-dozen or even several dozen quantities are all varying simultaneously and in subtly interconnected ways."»

To model and represent these factors and their interconnections we are implementing an ontology semantic. We are not committed to model each and every factor, but to support the designer in defining her/his significant factors and their interconnections, then freely exploring the dimensions of the space of the design solutions generated by the system.

The dimensions of the solution space increase with exponential law, thus the system is implementing:

- Ontology-based to orient the system knowledge towards a domain interpreted through rules of inference and logic approach;
- Generative system for exploring the very large number of design solutions (Garey and Johnson 1979).

This approach substantially differs from an optimization process, where the space of the solution is explored by a minimization algorithm in order to recognize the solution that best fits the given criteria. With the proposed methodology, the designer can explore the high-dimensional space of the solutions generated by the system according to the given constraints and criteria, in order to find the solution/s that best fit the implemented criteria but also further ones that the system is not considering, while the designer is. For instance the designer can be considering aesthetical criteria or ones relating to the site or the milieu etc. These additional criteria possibly are not implemented in the system explicitly.

## 2. Characters and complexity of urban design

We explore the urban design by process, considering it an ill-posed domain, bounded on one side by the requirements and on the other the strategies used by the designer, in order to define a frame for the complex and interconnected factors ranging from, for instance, principles, visual representations, numerical data, mediations, analysis, as well as quantitative requirements, urban regulations and standards.

We propose an ontology semantic system approach to bridge the representation of the factors and the designers (the end-users of the system).

The generative system supports the designers in simulating different urban alternative scenarios in relation to the uniqueness and constraints peculiar to a project or a site.

These factors produce different configurations relied with typological and measurable inputs, and generate a large number of solutions.

For exploring the high-dimensional space of design solutions the system offers both tools for searching it and for structuring it.

The system implements strategies and technologies for searching the high dimensional space of design solutions and for defining and presenting structures in the space of solutions. We do expect structures in the space of the solutions to be a promising methodology for more effectively supporting the designer in recognizing the "neighbourhood", where s/he expects to be the design solutions, then to explore this neighbourhood to evaluate the small variations in the constraints and criteria that defines them. To make the system more flexible we improve the semantic of relations with the ontology language. Thus the final aim of the generative system is not defining one, the best fitting solution, but to drive the designer towards one or more "neighbourhoods" in the space of the design solutions, where s/he can gather suggestions or directions in designs that otherwise s/he will possibly not have been considering.

3-D scenarios allow urban designers to explore the space of design solutions defined, for instance by typological, quantitative and performance factors. The simulation makes it possible also to structure the units in relation to different typologies (e.g. type and quantity). Thus we can explore the multiple simulations of scenarios to understand what happens to the system when we change the quantity of a specific typology for a site. Obviously this change affects the interrelated types.

We can verify the relations between the building placement and the ambient factors evaluating the daylight comfort for each building and unit in relation with its neighbourhood (Cheng et al. 2006). Our generative system is hybrid: a software seamlessly integrating the generator of a large number of design solutions and the browser for searching and structuring the high-dimensional space of the design solutions, according to variable and customizable factors defined by the designer. We constructed a system of rules and relations using ontologies. This approach allowed a flexible customization of the system to various requirements and situations. Indeed we could build a set of rules changeable to different requirements. Using the ontology logic and semantic the complex a set of rules has been intelligible by digital systems.

To this aim, we are dealing with different issues: all the factors considered cross various domain knowledge, from different competencies and sources; the knowledge is both semantic and procedural.

We are experimenting different strategies for the formalization of the ontology:

- top-down, starting from the general notions (meta-design in Bazzanella 1971) to the scale of the building, discredited in *voxels*;
- bottom-up, starting from the analysis of cases, defining several layers of ontologies (after Bradshaw 1992), each referring to a specific case, and then representing the overlapping information without having to build a general, wide domain ontology;
- a middle approach is possible (Uschold 1996), but we found less references to present design practices.

## 3. Related works

We are recognizing two principal directions of research in ontologies dealing with our approach to urban design.

The first explores ontologies as tools to ensure the cooperation between several urban actors and interoperability between different urban data bases. A system based on ontology is promising, because it allows dealing with the semantic dimensions of the urban design. An ontology can be defined as a semantic graph regrouping concepts (Keita, Laurini et al. 2004).

This research developed a prototype system -*Towntology*- able to navigate the ontology displaying its graphical form and query it. Several approaches were used for the construction of the ontology. They decided to work first on street planning and on mobility. Already more than 800 concepts (French language) are introduced in their ontology, with 21 types of relations between concepts. This study describes the difficulties of creating this ontology, and the way (tools) to solve the problem. The solution is to lay out specific ontologies for each actor (with each field), and a global ontology. Thus any request and data exchange must be done via these ontologies. The research works within the framework of the Towntology project aims at writing urban ontologies in a visual form. This visualization is a way to be explored towards a co-operative system. From the descriptive point of view of ontologies, an extension of XML is designed and used.

In this direction Metral's (2006) study aims to contribute to a better communication between the various actors involved in an urban planning process due to the complexity of the urban planning process. The research pones three goals:

Semantic Integration of the objects (data and documents) related to an urban planning project to create an urban knowledge base. Indeed urban data and documents (spatial data from GIS, 3D city models, texts, maps, plans, pictures) are represented in their system by an ontology with concepts and instances related to the data and documents so as to present an integrated view of the project.

The second purpose is to develop an interface to visualize the content of the knowledge base. They identify visual objects to define from the objects of the knowledge base. At the same time they describe objects of various kinds: documents, 3D objects but also abstract concepts to delineate representations for non geometric entities.

Third aim of this investigation is the adaptation of the interface to user profiles and centres of interest in order to access to the urban knowledge according to different viewpoints of various actors (urban planners and designers, politicians, citizens, communities, etc.) with differences in terms of knowledge background and vocabulary. They set an adapted interface, a system of visualization of what is useful or relevant to the user exploratory interface to understand an urban planning project in a personalized way.

The second approach defines a use of ontologies to exchange information between computers and to make the systems flexible for different domains of use.

Decision Support Systems (DSSs) (Schevers, 2006) can help clients, by presenting design solutions using virtual reality, and by offering relevant feedback such as costs, energy usage, distances and density. Using these systems, clients and stakeholders can run 'what-if' scenarios on different design solutions and see the consequences of their changes.

To make sure that a DSS is suitable, it needs to cope with the project situation at hand. This research investigates DSSs that can be built 'on-site' and that are flexible enough to model project-specific issues. A custom-built DSS can be tailored for each project. Therefore this study explores the use of ontologies. The use of an ontology enables further reuse of software components and software models. With this approach, several parts of software components can be reused and put together to quickly develop a customised DSS.

## 4. Ontologies for urban design

### 4.1 Representing knowledge

The design process needs an adequate communication to relate with the stakeholders, sharing ideas with the team, until the choice of the way to present the project. The knowledge representation of the system improves the research and definition of a language capable of expressing the specific knowledge and information used during the design process. From this perspective we can consider a model -system of representation- as a language capable to share and represent information. A model is not a 'picture' of the problem, but rather a device for the attainment or formulation of knowledge about it (Kaplan, 1963). Indeed, sometimes the most important outcome of the modelling process may not be the model itself, but rather the insight we gain as we struggle to articulate, structure, critically evaluate, and agree to it (Moore & Agogino, 1987). Therefore the purpose of the process is not only a proper representation of a system but rather how this process can help us to better understand the domain of knowledge represented in it.

"Conceptual modelling is the activity of formally describing some aspects of the physical and social world around us for purposes of understanding and communication. Such descriptions, often referred to as conceptual schemata, require the adoption of a formal notation, a conceptual model in our terminology. Conceptual schemata can also be used to communicate that common view to newcomers, through a variety of graphic and linguistic interfaces." (Mylopoulos,1991)

To support the digital tools for urban design being flexible to different types of designs, they must rely on a highly customizable and versatile language. This versatility can be pursued by a system grounding its components and attributes using an ontological model. The ontology represents a way to describe a standardized system of information and relations expressed in unambiguous vocabulary. The quest for large-scale knowledge sharing provides a strong motivation for common ontologies. Careful design of the ontology and the careful definition of the terminology also benefit developers and users of the system (Bradshaw et al., 1992).

Ontology, in the philosophical meaning, is a systematic account of existence as perceived by humans. “The more traditional term is Aristotle's word category, which he used for classifying anything that can be said or predicated about anything." (Sowa, 2000) “. One of the main roles of ontologies is to disambiguate, providing a semantic ground, a consensual conceptual vocabulary, on which one can build descriptions and communication acts” (Gandon, 2002).

The flexibility of ontology language structured on a consensual conceptual vocabulary makes it an ideal tool to share and operate with knowledge in A.I. domain. Klein (2002) defines an ontology as conceptualization of things in a computer interpretable format. By relating machine-interpretable information to each other, inference support can help consistency and can support further interoperability (Gruber, 1995).

### 4.2 Ontologies as urban systems

We agree with Coppola (2005) in transferring the design activity to the domain of A.I. is appropriate to clarify the design process. The process can be declarative or procedural. Declarative knowledge operates to verify operations, it reaches a more efficiency in terms of technological examination to allow a description of the computational process. On the other hand procedural knowledge works on the syntactic level, it improves more quality intended as propriety and suitability verification in relation with the domain to allow a description of design process.

We are dealing with two major aspects:

- transcription of a formal ontology, which represent urban design process;
- definition of a generative design methodology based on A.I.

To delineate the formal ontology we have to clarify the procedural paradigm of the system. We should define the process which describes the design (not its morphology). It is central for this stage comprehend the value of inference determined by the single choices along the design process. Therefore it is important perceive how each alternative can affect the further ones.

The exploration of tools for urban design process reckons the urban forms as organisation of spaces ordered by a system of relations and hierarchies making in their rapport a sort of language. A semantic with rules and structures.

The study has been divided in three principal steps:

- analysis of real cases to infer examples for defining the typologies;
- identification of some simple typologies which refer for all considerations about urban units;
- analysis of real existing buildings constituted of a mix of different typologies, according to these examples we define the relationships among typologies as parts of complex systems.

The semantic model includes specific information to arrange different units. For each typology are defined dimensional parameters as width, depth and rise. These values define dimensional ranges, that is categories within the dimensions varying between a maximum and a minimum, directing towards best fitting values. This way the designer can easily decide, further to her/his requirements, the optimal parameters that the system must pursue. This approach assures high flexibility and adaptability to different situations, whether external inputs defined by clients or economical constraints. Thus the designers can simulate and exploring a wide range of different solutions in terms of typology and dimensions.

Next pass has been defining the spatial relations which identify a building system. In this perspective the research has been oriented in analysing *simple* typologies infer from *simple* buildings. So a series of relations has been determinate for describing less complex systems which can be straightforward to be defined and represented. A number of typologies have been described from the semantic and conceptual point of view. Hence it is a set of relations which describe how each typology works outlining different groups of activity holding in diverse typologies (Coppola, 2006).

The research starts from the study of urban milieus, to highlight the organised and interconnected among space and built, parts of the city and functions. We thoroughly consider the structure of buildings, as a formalised system of relationships among instances. The analysis of real cases aims to explore a sort of system of rules which defines the base for generating a variety of buildings, differing among them, but pertaining to a common instance or class.

Therefore the relations between parts of the buildings have been analysed with the definition of an ontology model. With this kind of approach, it becomes possible describing connections among *simple* functions, i.e. unitary one. We define a set of conditions specified by the role of each part, in relation with the others and the whole building. This allows the ontological system to classify and organise parts and relations. This approach shows how each single part / function of a building must follow different rules according with its properties and instances.

The ontology has a high level of adaptability for describing multiple configurations and conditions. Thus it can express behaviours which are part of similar solutions but which produce different formal results. Through the ontology language we can manage quantitative value, which describe the typology dimensions according to other typologies. It is possible to explore relations occurring among typologies depending on quantities and dispositions. For instances with a fixed quantity of residential surface required, quantities and relations between elements present in the system will change according to the residential typology chosen.

As we consider the urban system the field of application of our research, this system can suggest us rules for development indeed as rules for alteration. The system can be highly customizable, to define real and specific cases. On the other hand it can demonstrate flexible in the research of solutions, to allow the exploration of creative solutions, far from ordinary results, suggested by the practice. Of course it permits to control all the input and verify possible irrelevant condition in imputing or organising data. Also is possible to rethink all the rules of growth which generated insignificant circumstances in way to revise the strategies of design during the design process.

## 5. System implementation

### 5.1 Ontologies representation

Now that the purpose and the scope of our ontologies have been stated, we need to explicitly represent in some formal language the conceptualisation captured. Typically, this will involve (Uschold, Gruninger 1996):

- committing to the basic terms that will be used to specify the ontologies (*e.g.* class, instance): they will form the meta-ontology of representational terms used to express the main ontologies;

- choosing a representation language, capable of supporting the meta-ontology;
- specifying the ontologies using the chosen formal language.

Following these guidelines we discovered that, at least for the ontology about the building typologies, a frame-based knowledge model is the best way to formalize the domain of interest.

We chose the Protégé software [Protégé], an open source knowledge-representation system, because it supports constructing and storing frame-based domain ontologies and also because it is widely known as a flexible, well-supported and robust development environment. It has been used in the past years in several successful projects and has also been used to implement a transcription of the Suggested Upper Merged Ontology proposed by IEEE (SUMO).

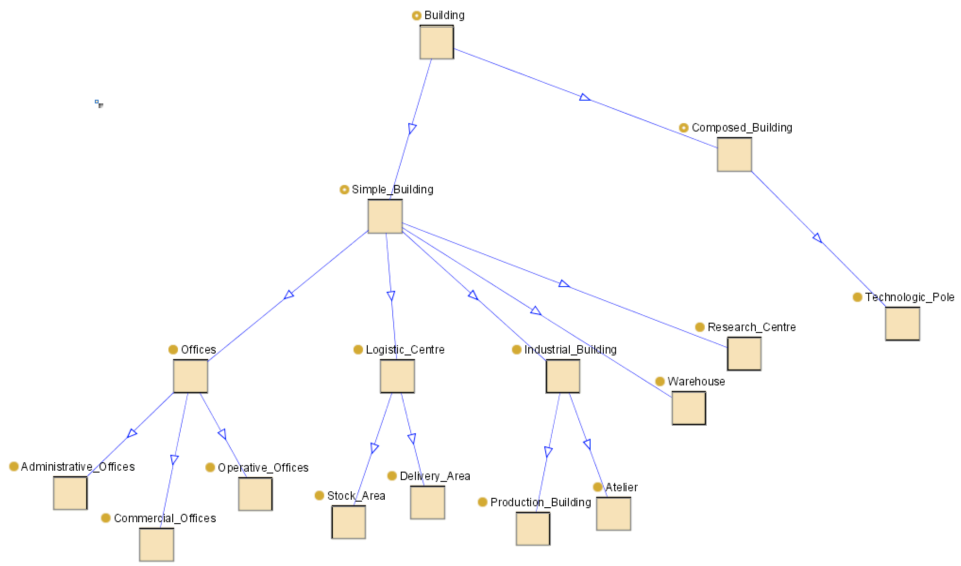


*Fig.1 The building typologies ontology coded in Protégé.*

The Protégé meta-ontology defines classes, slots and facets. Classes are concepts in the domain of the discourse and constitute a taxonomic hierarchy: the concept of *inheritance* let us to state that if a class A is subclass of a class B, then every instance of A is also an instance of B. Slots describe properties of classes and instances and are defined independently of any class; when they are attached to a frame, like a class, they can have a value. Facets are the way to specify constraints on allowed slot values; they include cardinality constraints, restrictions on the value type (*e.g.* integer, string, instance of a class), minimum and maximum value for a numeric slot, and so on. The restrictions defined in the facet apply to a single attachment of a slot to a class frame.

Using the Protégé meta-ontology as knowledge model for our building typology ontology, the hierarchy of the classes represents the ISA (subsumption, specialization) relations between the concepts of the domain. Other types of relations like PART-OF (aggregation), RELATED-TO (general association), and so on will be coded with slots; a substantial benefit in defining a formalization of spatial relations comes from a recently presented taxonomy of topologic, directional and proximity relations that we plan to introduce in our ontology (Mele et al 2007).

### 5.2.1 Interpreting ontologies

Elementary our generative system consists of the representation of the plots, rules and typologies that describe the methodology for aggregating the units in buildings/s, and evaluation parameters. The complete set of rules was defined by using the ontology model.

Protégé provides an interface which other applications can use to access knowledge bases. These applications need not use or display any of the Protégé user interface.

The programmatic interface to Protégé projects and knowledge bases is through the edu.stanford.smi.protege.model.Project class in the protege.jar file. This class has a getKnowledgeBase() method that provides access to the contents of the knowledge base. We enforced a closer mapping between our generative system and the Protégé model by importing in our inferential engine the original class structure of the ontology model. Protégé provides several mechanisms that generate such classes (Knublauch,2003). For example, you can directly generate Java classes for it with the BeanGenerator. We exported our model to UML and then generated Java classes with the Poseidon for UML tool. Poseidon product uses Velocity as a template tool in order to generate Java code from UML diagrams that you design using their tool.

### 5.2.2 Multi-agent model to develop morphologies from ontologies

We define rules as mandatory and non-violable set of constraints, which describe the urban regulations and the geometrical features of the plots. Besides, we consider on the same rank the area covered by the building and the layout of the site fitting the requirements of the design. Combining these parameters we were able to address the development and the distribution of the units into building volume/s on the site. The space of the design solutions generated is directly related to the mandatory rules, e.g. from the urban regulations as maximum height, distance from other buildings, etc.

Despite of a number of rules, the space of the design solutions is still high-dimensional. The space of the design solutions is generated by a multi-agent model. Agent-based modelling offers a flexible way to study the behaviour of mathematical models. In agent-based models the time evolution of all the system emerges from the level of the individual agent's action and behaviour.

Agent-based modelling has demonstrated effective in economic, social and natural sciences, and design (Gero and Fujii 1999), especially when it is not possible to define an analytic solution to the problem.

We designed and implemented the multi-agent model in Java Swarm environment (Minar et al. 1996). The input to the multi-agent model is generated by the relationships between "local" actors (e.g. the owners of the land, dwellings etc.), "global" actors (investors, public decision-makers etc.) and their interactions (market, social, etc.). We can simulate different urban dynamics at the building scale considering as input the following factors: typology, plot edge, total building volume, front and depth dimensions, floor number and height, number of buildings, minimal distance between buildings, minimal distance from the edge

The multi-agent model generates and evaluates the suitable solutions to the input problem which satisfy the hard constraints imposed by the input factors, considering as evaluation parameters the following: solar availability on building façade (irradiance performance), ratio between floor gross surface and open surface, ratio between floor gross surface and façade surface, ratio between floor gross surface and roofing surface, construction cost, land value.

After Hillier and Hanson (1984), we map the plots on a three-dimensional grid. For simplicity, we use a cubic grid (for instance, 1 by 1 by 1 m). On the other hand this simplification has demonstrated flexible enough to represent concave plots (e.g. in historical cities) or buildings with non Euclidean envelope.

We define a building agent for each building. Each building agent starts from a building with minimum, suitable layout and tries to optimize the layout adding new units-cells to the building. The starting seed location of building/s is random. We decided to use an exhaustive research strategy to exhaust the space of the design solutions, reducing pruning rules to a minimum. In this way we were able to generate a large number of initial, random seed solutions to explore unexpected solutions and relations between the units.

Since each building-agent can create a proper schedule, it is important that all of these activities are coordinated in a logical way. A top level agent schedules the action of each building-agent. The top level agent also manages the user interface, scheduling the updating of the graphical display (see figure 2).

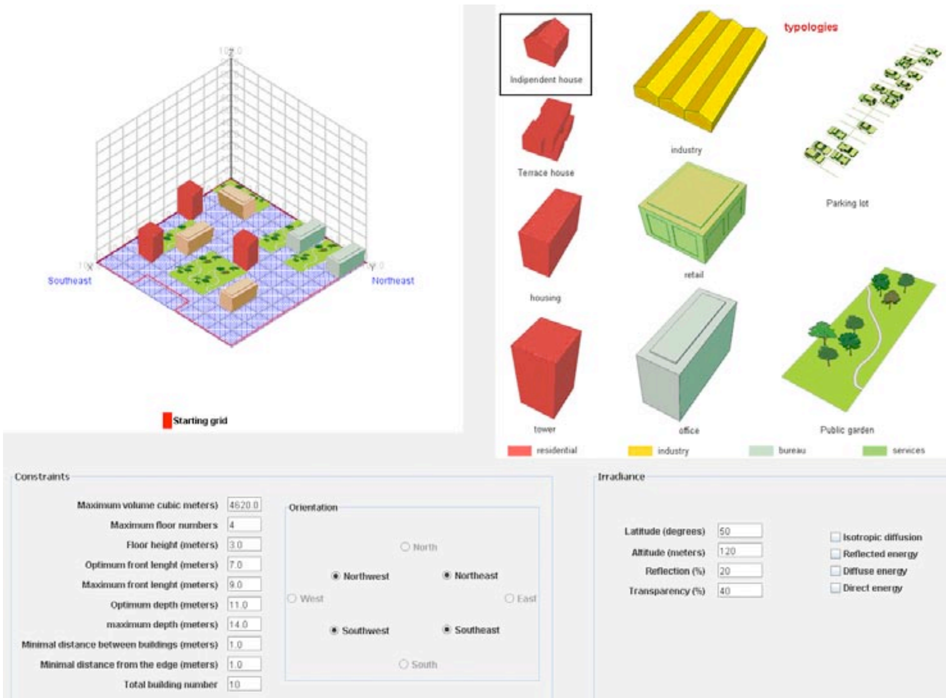


*Fig.2  The graphical user interface of the generative system*

This multi-level integration of schedules is typical of Swarm based models, in which the simulation can indeed be thought of as a nested hierarchy of models, in which the schedules of each agent are merged into the schedule of next higher level (Johnson 1999). The simulation proceeds in discrete time steps. As the simulation proceeds, the building agents update their state and report their state to the observer top-level agent. Auxiliary agents that facilitate the work of the building agents, can be instantiated if more than one typology is present.

The building agent uses a cellular automata to add cells to the building and communicates with the other agents in order to respect the hard constraints on distances between buildings. A cellular automaton is a collection of cells on a grid of specified shape whose state evolves through a number of discrete time steps according to a set of rules based on the states of neighbouring cells (Weisstein 1999).

Two of the most fundamental properties of a cellular automaton are the type of grid on which it is computed and the number of distinct states (usually represented with different colours) a cell may assume. We defined the cellular automata used by the building agents on Cartesian grids in 3 dimensions with binary cells representing the occupied/not occupied state. The user can decide the dimensions of each cell (for example front by depth by height = 1 m by 1 m by 3 m).

In addition to the grid on which a cellular automaton lives and the states its cells may assume, the neighbourhood over which cells affect one another must also be specified. In this case the most natural choice could seem the "nearest neighbours," in which only cells directly adjacent to a given cell may be affected at each time step. Instead, we decided to use the 3-d generalization of the von Neumann neighbourhood (a diamond-shaped neighbourhood), because in this way the automata update algorithm was less computationally expensive than the nearest neighbours one and able to accomplish the requested task.

The automata add a new cell in the position which maximizes the score. When the first floor of the building is completed the automata proceeds to complete the remaining floors. Each time a cell is added the building agent communicates to the top-level agent the new state of the automata. This process continues for each automaton until the total volume requested for the site is reached, as checked by the top level agent.

## 6. Case Project: Mirafiori Area in Turin

We have experimented the methodology and system in various case projects. Here we present a project at the urban scale: the possible evolution scenarios for the Fiat Mirafiori factory in Turin, Italy. The case project outlooks the conversion of a portion of the factory, since the Fiat Company has dismissed a slice of about 310,000 m2, of the total, huge area: about 3,000,000 m2. In the historical evolution of the site, the considered industrial area has become an integral part of the urban milieu of Turin.

The Mirafiori project may become an opportunity for the city to explore a number of possible scenarios both on the expectations on the production models and on the perspectives for the metropolitan area inserted in a larger network of cities. Thus we consider the case project as the act of exploring advanced indications, representing them beforehand by next-decades scenarios. The aim of these scenarios is not foreseeing future urban morphologies and policies, but to expose factors that can contribute to the shaping of a large area: making these factors visible, so that the various actors, involved or with responsibilities in the process, can recognize and weight them.

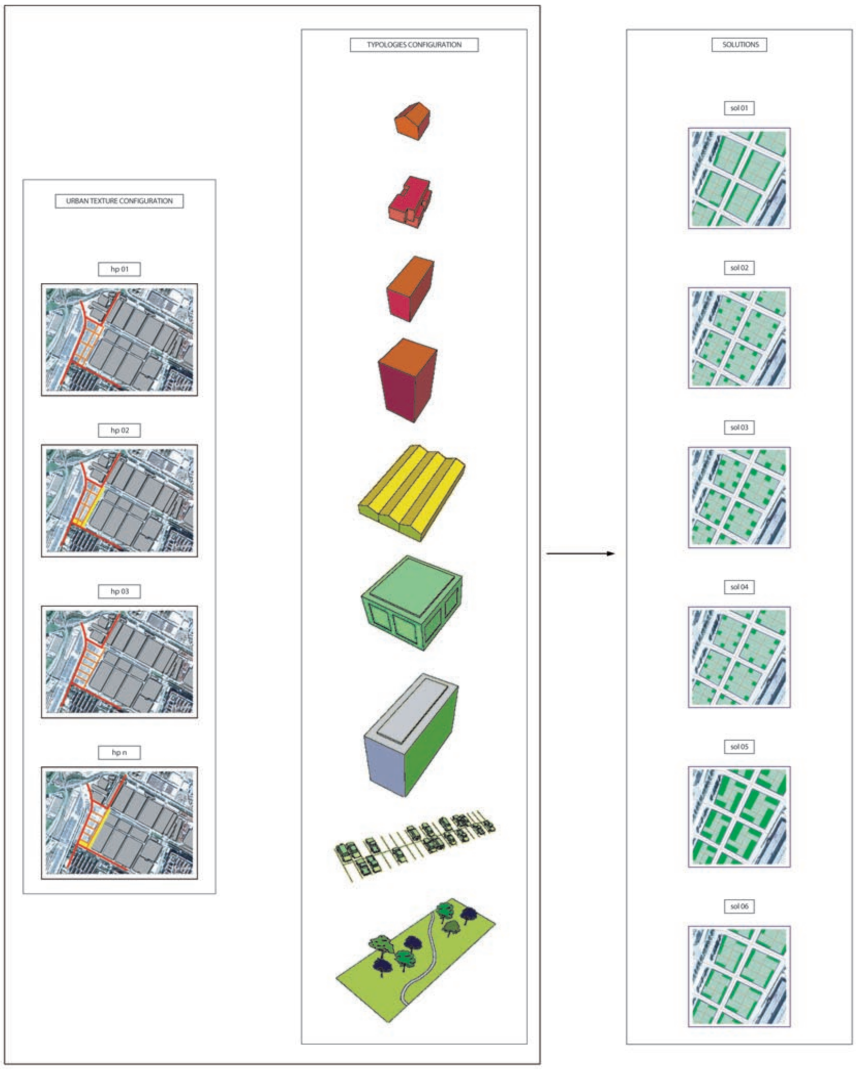


*Fig.3 Matrix representation of a set of future scenarios.*

The scenario making for this project has been a way of understanding the dynamics of the area and city, consequently trying to identifying the leading factors that can drive the dynamics.

The simulation of these scenarios with our generative system aims exploring:
a) the hypotheses regarding the future use of the area, as the result of an open decision-making process, aimed to define a strategic plan for renewing the site (Spaziante 2006);
b) the urban morphology as the subject of the scenario generation and evaluation, to support the designers', planners', decision-makers' and citizens' structuring and

describing of the relations between the factors that shape the morphology at the urban scale.

The simulations of the four scenarios with our generative system allow us making visible the relationships among alternative destinations, typologies, and variable volume, height, distance between buildings, plot edges etc. Using ontologies we built the set of relations between parts of the system. The ontologies have ensured the easy experimentation of different sets of alternatives. Different scenarios were implemented and simulated to explore the respective space of the design solutions.

## 7. Conclusions

The system aims supporting the early evaluation of alternative solutions from the initial phases of the urban design process. Especially the capability to rapidly generate alternatives is conceived to support design and planning practices, particularly during decision-making, because it can quickly represent alternatives and their interrelations (e.g. scenarios) into morphological, three-dimensional outcomes. The capability to explore urban design in 3D models allows the designers and decision-makers to verify the process at the full extent: it demonstrates a powerful tool for widening the discussion and participation among designers, planners, decision-makers and citizens.

According to our experience, often this meeting sticks the discussion into opposite positions that, in principle, can hardly find a balance. Instead the high-dimensional spaces of the design solutions generated by the system, starting from the ontological description of the some factors, can be used to systematically explore alternative and creative options.

Generating the large space of alternatives and visualizing them turns out really useful to outline both the interrelation between the factors and the borders between the possible and the unsuitable.

Ontologies can provide a specification of domain information by representing concepts and relations, this specification helps in building semantic information systems to support activities. Indeed we do expect ontologies to straight the interpretation and writing of the factors by designers, planners and decision-makers, allowing them to quickly and interactively change the concepts and their relations, for generating 3-D urban scenarios and exploring the space of design solutions.

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