URBAN GENERATOR

Agent-based simulation of urban dynamics

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Abstract. The paper presents an ongoing project to interactively simulate urban and regional dynamics at the building scale. Urban Generator is a system for generating a large number of design solutions and for browsing, searching and structuring the high-dimensional space of the design solutions further to variable and customisable factors defined by the designer. The number of these factors is recognised as large; furthermore they are often ill-defined. Urban Generator does not model every factor; instead it supports the designer in defining the significant factors and their interconnections, then freely exploring the dimensions of the space of the design solutions generated by the system.

1. Introduction

Urban Generator is a challenging prospective for exploring the numerous and often interconnected factors that can affect the urban design potentially. The number of these factors is recognised large, furthermore they are often ill-defined, and can assume different meanings relating to the urban 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 (1961) 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. »

Urban Generator is not committed to model each and every factor; instead it supports the designer in defining the significant factors and their interconnections, and then freely exploring the dimensions of the space of the design solutions generated by the system.

The dimensions of the solution space increase exponentially; thus the system is implementing strategies and tools for exploring the very large

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number of designs solutions generated (Garey and Johnson 1979). This approach substantially differs from an optimisation process wherein solution space is explored by an algorithm in order to recognise the solution best fitting 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 aesthetic criteria or ones relating to the site or the milieu etc. These additional criteria possibly are not implemented in the system explicitly.

The paper presents 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 recognising the "neighbourhood" where s/he expects to be the design solutions, and then to explore this neighbourhood to evaluate the small variations in the constraints and criteria that defines them. Thus, the final aim of the generative system is not defining one, best fitting solution; rather the aim is to drive the designer towards one ore 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.

2. Related Works

We are recognizing two main directions of research in CAAD dealing with our approach to urban design. The first puts forward tools for supporting the design process. The second generates designs of urban configurations.

To the first direction relates tools for the support of the various scales, models and disciplines in urban design. From the building scale, for instance models focusing on the simulation of the thermal performance of buildings. Bouchlaghem (1999) advances computer models not only for simulating the thermal performance of the building taking into account design variables related to the building's envelope and fabric, but also applies numerical optimization techniques to automatically determine the optimum design variables, which achieve the best thermal comfort conditions. The main optimization program is supported by a graphical model for the design. The models offer a valuable decision support system for designers at an early design state for the optimization of the passive thermal performance achieving optimum thermal comfort and savings in heating and cooling energy.

Development simulator is a decision making support system, which helps urban designers and architects, along with developers, city officials. It integrates two tools: a calculating tool and a form shaping tool. As a calculating tool, it helps designers do calculation, computation and estimation. Given criteria, it helps designers to search for the optimal result. As a form-making tool, it gives direction to building form driven by the results of calculation, computation and estimation. (Samiaji 2001)

An early contribution to the second direction of research is Hillier and Hanson's (1984) basic model of the evolution of urban configurations, where every plot is discretised on a bi-dimensional grid.

A further contribution comes from shape grammars, for instance Mayall and Hall's (2005) work, which uses a vocabulary of landscape object types and spatial syntax rules, and these can be used to generate scenes.

There is also an algorithmic design of architectural configurations, relating to the capability to rank different alternatives: Fuhrmann and Gotsman (2006) consider computing the merit of a given configuration of units, to generate configurations by "greedily adding and removing units with the aim of maximizing the merit of the resulting configuration, either in a planar or a spatial setting".

3. Urban Generator

Usually we pay attention to what happens between the design process in architecture with all its requirements and the strategies used by the designer to work into it. Certainly urban design incorporates complex factors which comprehend multiple principles, including visual representations, numerical data, mediations, analysis. Generally we have to compound the accomplishment of quantitative requirements: to fulfil the urban regulations and to satisfy the qualitative standards.

Urban Generator is a system for simulating different urban 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 (cf. 6. Value results. A cluster analysis of solutions).

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 impact of the sun irradiance on the buildings to estimate not only the cast shadows and the daylight illuminance, but also perceived qualitative aspects as daily solar and sky visibility access. Consequently the system evaluates the solar potential for each point of the plot depending on the shape, size and place of the buildings. Thus it is possible to evaluate the daylight comfort for each building and unit in relation with its neighbourhood (Cheng et al. 2006). Urban Generator is a hybrid system, 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 customisable factors defined by the designer.

4. Typologies

We understand architectural typology as a methodology to express the designers' awareness of basically different design options, according to their understanding of their appropriateness to various desires and requirements, or also the combination of several diagrammatic representations and characters structured into recognisable pattern. (Van Leusen 1996).

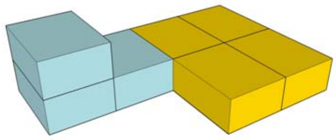

Figure 1. Road maintenance centre, Barré Architectes, Pleuguéneuc, France.

We have been analysing different building typologies for exploring the rules that can gather their shape and dimension into recognisable patterns. This way we are able to define the common reference elements to formulate evolutionary and associative grammars for each typology (see Figure 1).

We presuppose buildings discretised on a grid, so in order to describe typologies we use unitary volume parameters as height, length and depth (the number of cells on the grid). Thus we defined grammars which the system has to meet for aggregating the cells.

5. Rules as Design Process: The Multi-Agent Model

Elementary the 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.

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 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 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:

1. Typology
2. Plot edge
3. Total building volume
4. Front and depth dimensions
5. Floor number and height
6. Number of buildings
7. Minimal distance between buildings
8. 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:

a. Solar availability on building façade (irradiance performance)
b. Ratio between floor gross surface and open surface
c. Ratio between floor gross surface and façade surface
d. Ratio between floor gross surface and roofing surface
e. Construction cost
f. Land value

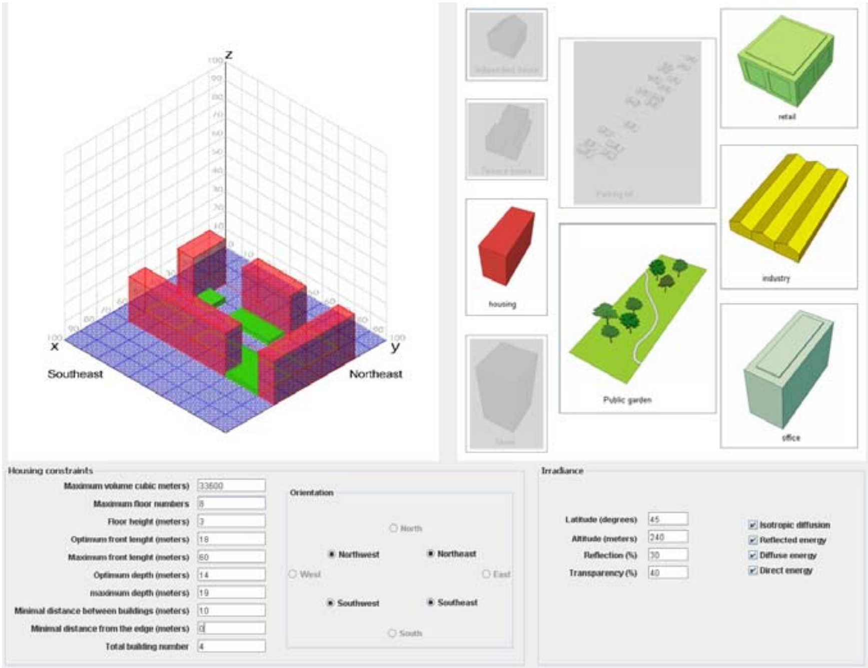

Figure 2. The graphic user interface of Urban Generator

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.

The building agent uses cellular automata (cf. next paragraph) to add cells to the building and communicates with the other agents in order to respect the hard constraints on distances between buildings. 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).

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.

5.1. THE CELLULAR AUTOMATA

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, see Figure 3), because in this way the automata update algorithm was less computationally expensive than the nearest neighbours one and able to accomplish the requested task.

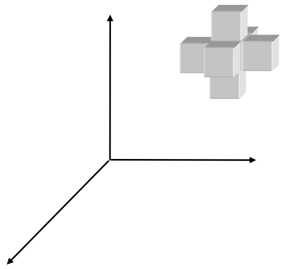

Figure 3. Three-dimensional von Neumann neighbourhood

For instance, we based the update rule for the “single family” typology on the relationship between the cost *C* and the building dimensions depth *D* and front *F*. Starting from this relationship a score *S* was assigned at each pair of values *D* and *F* by means of the following quadric in the 3-D space (depicted in Figure 4), i.e. the product of the score S_1 for *D* and the score S_2 for *F*:

$$S = S_1 \cdot S_2 = (a_1 \cdot D^2 + a_2 \cdot D + a_3) \cdot (\alpha_1 \cdot F^2 + \alpha_2 \cdot F + \alpha_3) \qquad (1)$$

We set the values of the coefficients (a_1, a_2, a_3) and ($\alpha_1, \alpha_2, \alpha_3$) so that the scores S_1 and S_2 were both equal to 0 for D=8 m, D=14 m and F=5 m, F=9 m respectively, and both equal to 1 in the maximum (we assigned a dummy value v<0 to S if D<8 m or D>14 m or F<5 m or F>9 m).

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.

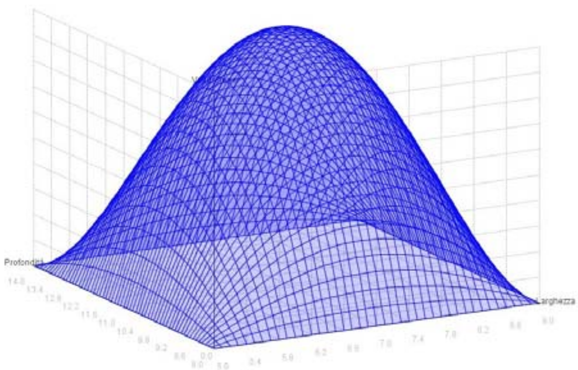

Figure 4. Construction cost function

6. Value Results. A Cluster Analysis of Solutions

The challenge is to design a formal solution which fulfils each normative requirement but also improves the qualitative standards. Measuring the idea of form and sustainability, as agreement with a regulated context, results being the balance among different aspects of a project in an urban milieu. These aspects are sometimes independent, sometimes interdependent and they have distinctive criteria of evaluation. They are related, so the increase of one's score determines the other's decrease.

It is important in the generative process that some constraints are stronger and more relevant than others, which means that the complexity of the factors can be structured and then reconciled with a hierarchy of decisions. Furthermore we must filtrate out the data because the dimensions of the space of the design solutions are high. If the space of the solutions is not ranked or structured, it demonstrates intractable and useless for the designer. We investigated the methodologies to rank and structure the space of the design solutions, setting relationships between urban regulations, sustainable practices, construction costs, and land values. We had to integrate the peculiar aspects of the various strategies to integrate the evaluation parameters with the normative constraints.

We created views on the high-dimensional space of the solutions to cluster different/alternative design scenarios, according to the designer's defined hierarchy in the factors. The clusters are defined homogeneous groups of design solutions in the view of the defined factors, e.g. solar availability on building façade (irradiance performance), ratio between floor gross surface and façade surface, ratio between floor gross surface and roofing surface etc. Cluster views demonstrated intuitive for a visual, prompt recognition of different groups/alternatives in design. The post-evaluation of the space of the design solution gives the system directions for generating further solutions, which can consider deeply the use of the plot or the density and distribution of the buildings on the site. At the same time, the designer can direct the guidelines of generation of the whole system in order to deepen the evaluation of these parameters.

The system implements further visualization techniques: 3-d scatter charts using glyphs and parallel coordinates.

Glyphs are a multi-variant analysis tool, which can be used as an effective way to represent the relationships between more than 3 variables in a single, comprehensible view. Besides the x, y and z axis the glyphs view uses the dimension of the glyphs (height, diameter, etc.) and its colour to allow rapid comparisons between the variables (see Figure 5).

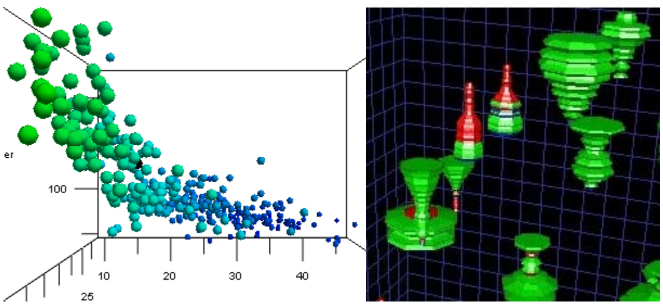

Figure 5. Glyphs.

The resulting image would resemble a room of floating glyphs. The room could be rotated, and the relative size, shapes, positions, and colours of each glyph could be observed. In a single image, the use of glyphs allows a researcher to absorb a large quantity of information easily (Visual and Spatial Technology Centre).

Parallel coordinates were proposed by Alfred Inselberg (1984) as a new way to represent multidimensional information. A parallel coordinates visualisation assigns one vertical axis to each variable, and evenly spaces these axes horizontally (see Figure 6). This is in contrast to the traditional

Cartesian coordinates system where all axes are mutually perpendicular. By drawing the axes parallel to one another, one can represent data in much greater than three dimensions. Each variable is plotted on its own axis, and the values of the variables on adjacent axes are connected by straight lines. Thus, a point in an n-dimensional space becomes a polygonal line laid out across the n parallel axes with n-1 line segments connecting the n data values (Goel 1999).

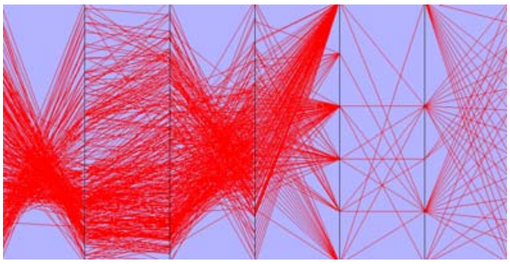

Figure 6. Parallel coordinates

Many such data points (in Euclidean space) will map to many of these polygonal lines in a parallel coordinate representation. Viewed as a whole, these many lines might well exhibit coherent patterns which could be associated with inherent correlation of the data points involved. In this way, the search for relations among the variables is transformed into a 2-D pattern recognition problem, and the variables become amenable to visualization.

7. Case Project: Mirafiori Area in Turin

We have experimented the methodology and platform in several 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 reconversion of a portion of the factory, since the Fiat Company has dismissed a slice of about 310,000 m^2, of the total, huge area: about 3,000,000 m^2. 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 recognise and weight them.

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. Figure 7 synthesises a set of the factors along two main axes: the horizontal axis represents the degrees of uncertainty between the demand-density for the area; the vertical axis represents the uncertain of the model of evolution (economic and social mainly) in the next decades, which involves not only the dynamics of industrial production, but also new opportunities to create places to live and to exert an influence on the very shape of the city.

The simulation of these scenarios with Urban Generator 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.

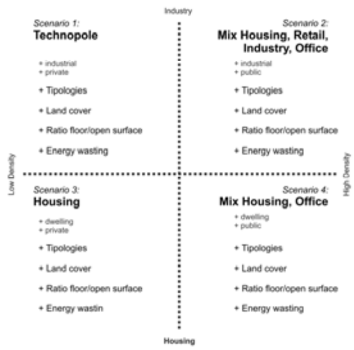

Figure 7. Matrix as a set of scenarios for the future.

The simulations of the four scenarios with Urban Generator allow us making visible the relationships among alternative destinations, typologies, and variable volume, height, distance between buildings, plot edges etc. (cf. 5. Rules as design process: the multi-agent model).

Each scenario was implemented and simulated in Urban Generator to generate the respective space of the design solutions. Figures 8 and 9 illustrate a glyphs view on the high-dimensional spaces of the design solutions and the inputs to and outputs from Urban Generator for three scenarios: 2. Mix Housing, Retail, Industry, Office; 3. Housing; 4. Mix Housing, Office. Figure 2 presents Urban Generator simulating one block in the framework of scenario 2.

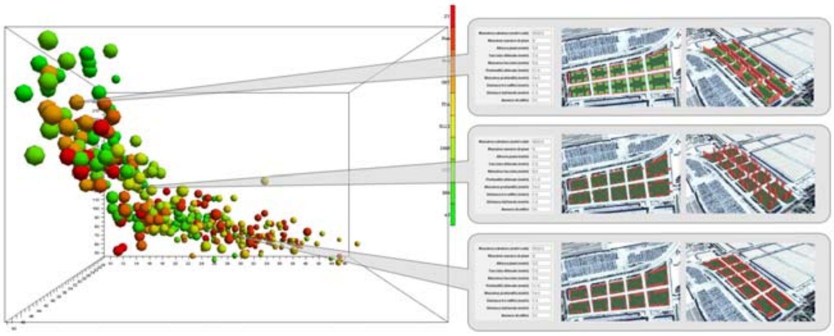

Figure 8. Glyphs view on three scenarios simulated with Urban Generator.

8. Conclusions: Exploring Design Alternatives: A Tool for Decision Making

Urban Generator aims to support 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 these meeting stuck the discussion into opposite positions that, in principle, can hardly find a balance. Instead the high-dimensional spaces of the design solutions of Urban Generator can be used to demonstrate that there is not a unique solution, instead there is a large space of alternative and visualising them is very useful to outline both the interrelation between the factors and the borders between the possible and the unsuitable.

Urban Generator can help visually estimating the morphological outcomes and interrelations in urban regulations. It can assist planners in verifying regulations not only from a quantitative point of view or a bi-dimensional one, instead from a full three-dimensional perspective. It has demonstrated useful in stressing and exploring the application of a regulation and also the interrelations among a specific regulation and further ones.

Figure 9. Scenarios 2, 3, and 4. Inputs to and outputs from Urban Generator.

Last, but not least, the experimentations of Urban Generator in real projects has opened a plethora of issues. Just to mention the main ones, the typological representations have to be improved, as well as the interrelations among different typologies in the same plot. Also the interrelations among different, adjacent plots considered simultaneously by the system have to be reconsidered. On the usability side, considered the prompt capability to generate vast amount of alternatives, the users-designers would really appreciate representation tools that will go beyond the structuring and visualising of one space of the design solutions, while they are requesting tools for comparing the interrelations/differences between variable factors and the resulting different spaces of the solutions.

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