

Semantic Analysis and 3D Generation of Buildings and Cities

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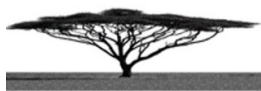
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# Semantic Analysis and 3D Generation of Buildings and Cities

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*The Urban Ontology implementation of buildings and cities, say the urban fabric, is described as a structured formal knowledge composed of both (1) a group of elemental portions of urban fabric, defined urban elements, and (2) a set of relations between those urban elements. Afterwards we present the UrbanGen system that interprets the Ontology to generate portions of urban fabric. The software allows the user to vary some urban elements or relations, and to verify new urban fabrics that are generated; at this point of the process, the phase of verification of the method and the phase of design overlap. In order to highlight the potential of the method used, and to verify the correctness of the determination of the body of knowledge, we set up the inverse exercise of the construction of urban fabrics through the use of UrbanGen. To this aim, we analyse some existing urban fabrics, and deconstruct them, reducing them to individual urban elements and relations that bind them. UrbanGen introduces and uses the urban template to model the requirements and the options of projects. An application to generate and evaluate design alternatives for an eco-industrial park is presented and discussed*

*Keywords: computational intelligence-based decision support, Modular Façade, Optimization Approach*

Keywords: ontology (computer science), knowledge representation, generative design, building morphology, city morphology

## 1. Introduction

Studies about building and city morphology, and about its roots with typologies, represent an important part of IT research in urban and architectural design, at least since the beginning of the second half of the 20<sup>th</sup> Century. The general purpose of this branch of studies, which had anyway very different declensions in the various cultural environments where they were carried out, is the attempt to capture the whole set of rules on which the construction of the city – with its manifold outcomes – is based. Moreover, there are at least two features that seem common to most of them.

First, the rules that are investigated in these studies are only sometimes explicit (the laws, the regulations etc.). Most of them are instead implicit, written in customs and traditions, and sometimes

also directly connected with specific local cultures. These systems of rules, regulations and procedures therefore define, a very complex knowledge base, whose character is partly mandatory (i.e. referred to a system of binding prescriptions) and partly optional, more related to the habits of a specific culture in a specific time. In this sense the knowledge about urban space is closely related to the recurrence of certain types of solutions, or – following the thinking of Guido Canella [12] – to the concept of “invariant elements”, seen as the “specific configuration” of a particular succession of events.

“I still remain persuaded by some definition attempts I made [...]: morphology as a ‘succession of events expressed in an historical context from time to time spatially defined’; typology as ‘the specific configuration resulting from a particular succession’ and, then, as a ‘methodology for seeking the morphological invariant element’. Therefore the ‘invariant choice’ is ‘influenced by the values assumed’ constituting a ‘downright model of culture’ and, in other words, the architect’s philosophy”. [12, own translation]”

Second, the study of the morphology, both when it has been carried out with a particular reference to the historically consolidated city [56, 14], and when it has been conducted on the more recent results of suburbanisation [80, 55] constitutes not only a useful tool to analyse and explain the generation of buildings and cities, but also a powerful instrument to guide the design of new parts of the urban fabric.

The aim of the present work is to connect with this branch of studies, exploiting the potential and the versatility of Information Technology, using the digital instrument for:

- Expressing and implementing a knowledge-base about buildings, urban spaces, and their components.
- Developing the UrbanGen app to generate automatically a ‘cloud’ of designs, from the knowledge base and from a set of peculiar circumstances and requisites.
- Evaluating the generated collections of design scenarios, filtering the results set with different performance variables (such as the insulation, energy efficiency, etc.).
- This work is based mainly on the Artificial Intelligence technology, in particular on the construction of the Urban Ontology (discussed in paper), which could be seen as an attempt to translate the general morpho-typology studies results into a human-computer dialogue technology, able to perform a human, machine aided design process.

UrbanGen could be understood both as a methodology (since we are defining a knowledge base and a method of complete description of the urban space and of its possible variations) and a technology (since we are implementing a software system, which can be used as a working tool in supporting design processes and decision making). The main advantage of the app is that it could generate in a very short time (thanks to computation power) a cloud of many significant solutions – each matching the general rules of the ontology and the specific requests and features of the individual case project. Visual analytics is implemented to ease and support the designer’s choice of the solution/s that fit the designer’s criteria.



## **2. Related Work in Generation of 3D Cities**

Modelling cities in three-dimensions has gained momentum, because of motion pictures, video games and virtual reality, as well as urban studies and simulations. 3D modelling a virtual city which is detailed enough to satisfactorily convince the audience, is a cumbersome task that can sum to thousands of hours of work.

A number of generative procedures have been developed to ease and expedite the modelling of cities. At present procedural modelling systems, grammars and scripting languages are commonly used to implement a set of rules to generatively describe urban environments [48, 39, 81].

The procedural systems have gone through evolution and specialisation [59, 33, 78]: L-systems, Shape Grammars, and Split Grammars.

### **2.1 L-Systems**

These were introduced by Lindenmayer [61]. Originally, they were applied to the generation of natural organisms and phenomena, for modelling vegetation [17] and fractal structures [47]. L-System defines a set of symbols, coded into strings, and production rules. A parser interprets the initial string, according to the predefined set of production rules, to form new, larger strings. The obtained string is translated into shapes through a transformation procedure. Parish and Müller [59] used them for generating street networks, “L-systems have been used in a similar application [...], support branching very well and have the advantage of database amplification [...]; this suggests their potential use to generate convincing large-scale road patterns”. Parish’s and Müller’s CityEngine uses two sets of rules: (1) global goals, the given hierarchy of streets, connecting density centres, and the given geometric pattern; and (2) local constraints, roads are pruned or rotated to fit inside legal areas, and are checked to fit crossroads within a given distance.

### **2.2 Shape Grammars**

These were developed by Stiny [70, 69]. They use production rules, but instead of operating on strings, as in L-Systems, they operate on shapes directly. The matching rules, e.g. mirror, rotation, scale, translation, are applied on an initial shape. The resulting shape is generated by rules applied in an iterative manner. Usually, at every step of the iteration, several different transformations can be applied, matching a set of various rules, thus potentially generating a large derivation of resulting shapes. They have been successfully used for generating buildings, since the pioneering works of Koning [40], Flemming [22], and Duarte [18]. In a seminal work, in 1978, Stiny [71] implemented a parametric shape grammar to generate the ground plans of Palladio’s villas. The grammar goes through rules for the generation of: (1) ‘tartan’ grids with bilateral symmetry that are used to fix the fundamental structure of the plans; (2) interior spaces in Palladio’s uniaxial shaped villa plans, the rooms being formed by iteratively joining together the rooms within the partition pattern; (3) realignment of the interior partitions to the north-south and east-west orientations; (4) principal entrances; and (5) even-ness and symmetry in the window openings.

Muller et al. [86] evolved the rule system of shape grammars into Computer Generated Architecture. It is a generative methodology applied to façades. The procedure starts with the mass volume of the building, including the roof. The volume is iteratively subdivided into sub-masses and sub-shapes. Generative rules account for context sensitivity by offering dedicated language elements for: “(1)

testing spatial overlap (occlusion) and (2) testing nearby important lines and planes in the shape configuration (snap lines).” [54]. The system implements context sensitive rules on entities, according to a hierarchical shape description. The hierarchy goes through mass, sub-mass, façade, sub-shape, and at conclusion inserts windows, doors, and ornaments. The main innovative achievement of Computer Generated Architecture is the formal implementation of a generative procedure into a hierarchical structure that makes it apparent to and readable for designers.

### 2.3 Split Grammars

These were advanced by Wonka [85], as an evolution of shape grammars. The methodology recursively replaces a shape with zero, one, or multiple other shapes, according to a mechanism of automatic rule derivation. The early split grammar, developed by Wonka, focused on the generation of façades, with size-independent design rules, applied through splitting operations. Hence the name ‘split grammar’. The size-independent design rules go through the placement of a splitting plane to rule a change into an elementary shape change. Several splitting planes can be assigned in sequence to chain series of rules. Split Grammars were further developed by Müller et al. [54], and implemented in the commercial software CityEngine [83]. Schwarz and Müller [64] further evolved them implementing the full recursive generation of the shape into a tree that makes the procedural generation fully manageable. The tree representation brings a wide spectrum of contextual information about the shape and the context that can be used by context-sensitive rules for managing the derivation. Moreover, a tree spanning algorithm was implemented, to explore and evaluate multiple generative alternatives, instead of singular ones, as in shape grammars.

### 2.4 Ontology-Based Generation

There have been few explorations of the generation of cities in three-dimensions based on ontology.

Liu et al. [44], to model buildings, proposed to express the architectures formally as ontology domains, with two main components: (1) a set of basic vocabularies and (2) a knowledge library of rules. The basic vocabularies store elements or basic components of architecture. The knowledge library comprises rules to control the generation, combination and construction of the basic components. The knowledge, to implement generative rules, is gathered from experts, e.g. architects and historians. Hence this body of knowledge can be redundant, conflicting, and partially overlapping. The translation of the knowledge into rules is an ill-posed problem, thus Liu et al. [44, 45] opted for the multilevel approach on ontology. The implemented ontology is a specific conceptualisation of Guarino’s definition of ontology [29], the proposed granular ontology is the approximation of conceptualisations and conceptual-relation granules, ordered as tuples. Their architecture ontology includes a series of architectural categories, components, and relations that aims to systematically describe a specific architectural style [Figure 1]. “For example, the concept of ancient Chinese architecture can be defined by the answers to the following three questions. Which kinds of architecture can be classified into the ancient Chinese category? Which components constitute the ancient-Chinese architectures? What kind of relationships are maintained in these components? A good ontology for ancient Chinese architecture should cover all the instances of that style.” [44]. The authors define a roughness function, to measure the degrees of approximation between a set of basic architectural vocabularies and a certain architecture domain. If the monotonicity of the roughness functions is satisfied for a given set, a heuristic algorithm can be applied to match a suitable rule set to assist in integrating the parts into buildings. Liu et al.

implemented a set of basic vocabularies and a knowledge library of vernacular architecture in the Southeast of China.

Bellotti et al. [2] advanced the three-dimensional reconstruction of cities, extruding them from two-dimensional maps, and generating the façades to the volumes “by statistically assembling sample images of architectonic components from the target city.” The architectonic components are categorised according to “classic principles of architecture” in ontology. The ontology represents a façade as a tree of elements, i.e. the structural and ornamental ones. In the ontology, the elements are divided horizontally in floors, and the generation procedure combines them [Figure 2]. The elements are selected and represented according to their evidence to human perception. “The ontology corresponds to an architecture grammar inspired to the classical principles codified by Vitruvius and then further developed by the tradition.” Various “architectural styles” are implemented in different ontologies and algorithmically applied to the extruded volumes in specific areas of the cities.

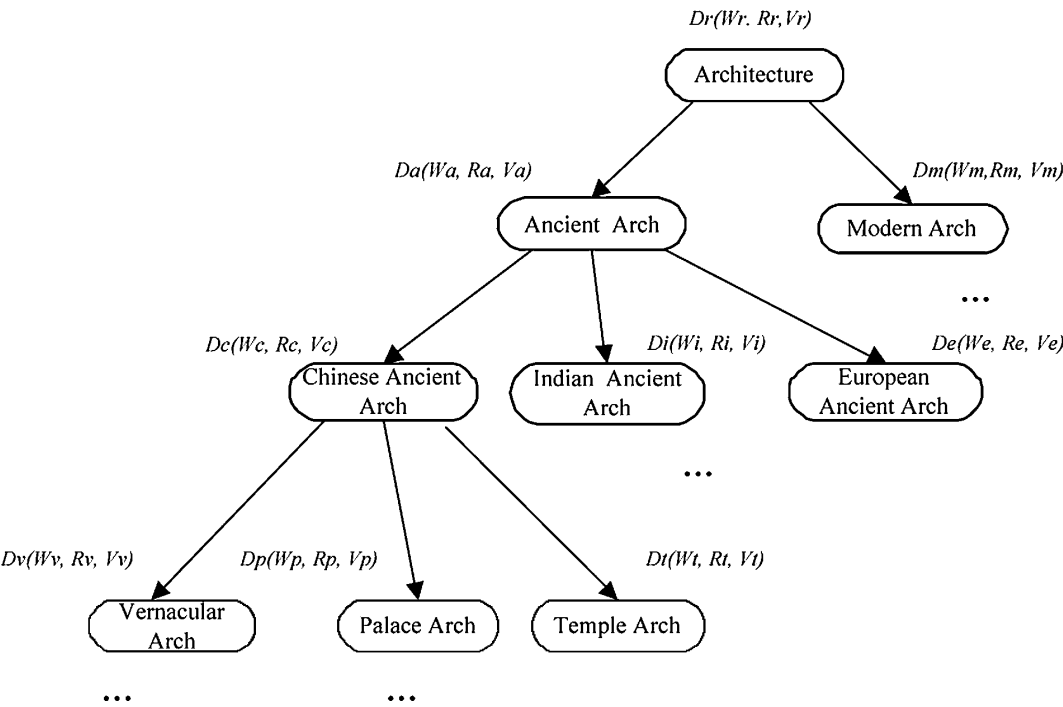


Figure 1. In Liu et al. [44] the domain concept tree for the ontology represents a series of architectural categories, components, and relations to systematically describe a specific architectural style.

Yong et al. [87] used ontologies to improve procedural modelling in digital architectural heritages. After Liu [44], to generate an architecture with a specific style, the ontology semantically implements (1) an entity set of the basic geometrical units in the procedural methods, (2) a knowledge library of the procedural rules, and (3) a transferring function among the knowledge library, entity set and model instances. Yong et al. extracted all of the procedural rules manually by

architectural practices, thus the rules can gather a certain degree of empiricism and imprecision. Consequently, the knowledge library embodies a redundant set of procedural rules. The proposed procedural methodology superseded the dichotomy between basic units in vocabularies and procedural rules, by means of a hierarchical ontology tree of components, to construct the set of entities. In the tree, the basic units were formalised in semantic XML description, and the characteristics and relationships among the components were represented in the ontology knowledge library. Tools and protocols for concept representation, from ontology engineering, were used to differentiate similar concepts in the rules. The hierarchical conceptions of the architectural categories in the tree allowed the authors to implement ontology operations for branching parental concepts and similar concepts.

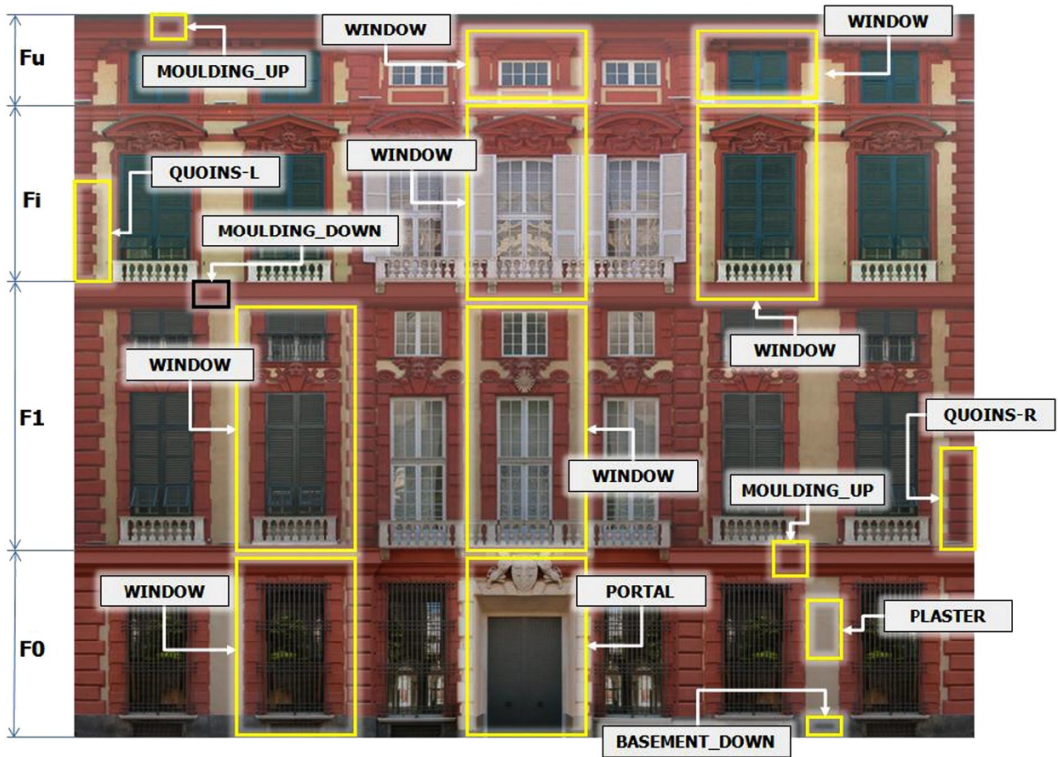


Figure 2. In the ontology the façade is represented as a tree of elements, divided horizontally in floors, the generation procedure combines the elements [2].

### 3. The quest of communication for planning and design

Three-dimensional models of cities for motion pictures, video games, and virtual reality pursue visual realism. The film director James Cameron has described his commitment in shooting *Avatar* as “the seduction of reality” [19], meaning that he aimed to deliver an experience with such a level of detail and textured appearance of materiality that “audiences could surrender completely to it”.

Christopher Nolan, directing *Inception*, for the meanings of the plot wanted to achieve a “tactile realism” [60]. To attain this objective, he blended shots of the characters in real locations with digital effects. For the famous scene of the bending street in Paris, in which the urban environment folds up into a cube containing the actors (Figure 3), Lidar VFX did a scan of about four blocks of the city at millimetre resolution. From the highly detailed data, the digital crew spent some weeks documenting and 3D modelling the Paris location. They implemented innovative ‘pertex’ texture mapping techniques, to ease the texturing of the façades and of the roofs in the model of the city that finally was animated with models of cars and people.

One of the aims of computer graphics, since its ‘heroic age’ in the sixties, has been to achieve much higher levels of perceptual realism, in making pictures that are indistinguishable from reality. This is crucial for all the applications where visual truth is relevant [52].

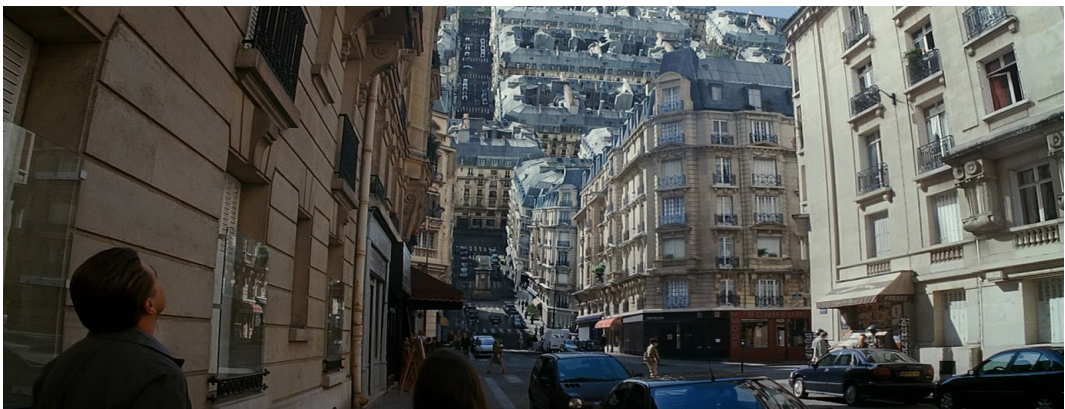


Figure 3. The folding street in Paris, screenshot from Christopher Nolan' *Inception* film (Image courtesy of Warner Bros).

“Digital representation of space, especially the computer visualization medium, is strongly influencing the way we understand and simulate the city and new designs” [57].

For the purposes of planning and design, the definition of the appropriate level of realism and of detail in the representation of cities pertains to the aims of the communicative action. “The visualizations have to be able to interpret some issues exactly (Drettakis et al., 2006), while merely sketching others (Lange, 2005). In some cases, a small to modest amount of detail is sufficient for obtaining the level of realism needed to operate the tool (Pettit et al., 2006). Others conclude that graphical complexity is preferable to a loss of information in detailing (Ostermann, 2010; Stahre et al., 2008). If the information is too complex, contains too many parameters, or is too abstract, it will be difficult to grasp” [7].

The generative procedures considered so far mainly deal with the visual appearance of cities: the façades out buildings' volumes, arranged along a simplified network of roads. They generate a vast amount of details in the 3D model to convey a sense of realism in the observer. Often all this detail is not part of the planning or design process and is not in the designer's control. “The strive for photorealism that drives the technical development within computer graphics is not always in

concordance with the need within urban planning to create trustworthy virtual environments for conveying understanding for the proposals. Instead, to create trustworthy virtual environments in the process of forming a design idea, there is a need for different expressions and levels of detailing in the representations” [7].

That’s why we have implemented a generative process that can benefit from the large body of knowledge that has been developed within the urban studies field, and would put forward ontology, as a knowledge engineering process, to capture and formalise the knowledge for architects-planners and computer uses.

#### 4. Methodology of knowledge analysis and conceptualisation

In 1999 Mike Batty outlined the leading aspects for the study of the morphology of cities: “the concern for process, the need for a consensus concerning appropriate descriptions of urban form at its most elemental level, and the need for formally consistent ways of classifying spatial and temporal relations. [...] linking structure to process, establishing basic units of morphological description, and deriving spatial relations consistent with the underlying geometry of cities” [1].

The present chapter focuses on what Batty has defined as structure of cities, which closely pertains to the definition of *tissue*, “Urban tissue type. Within an homogeneous historical domain, the conceptual project corresponding to the aggregative system of several building types, which the operator shares with the other members of the community” [14]. Anne Vernez Moudon, who wrote the introduction to Caniggia’s book, further clarifies the definition: “Tissues are groups of buildings, open spaces, lots, and streets, which form a cohesive whole either because they were all built at the same time or within the same constraints, or because they underwent a common process of transformation” [53].

Accordingly, the urban fabric should not be understood as the study of only the built, nor only of the unbuilt. Instead, it is the result of the mutual integration of built form and unbuilt space, especially of their reciprocal influences in contributing to the quality of places.

Conzen [16] considers:

“In the past many studies of plans have been restricted to the consideration of the streets or street spaces only, a method which has its roots largely in an earlier architectural preoccupation with the contrast between ‘voids’ and ‘solids’ and its aesthetic implications. The internal structure of street-blocks has generally been ignored as if this were not geographically relevant. Moreover, a certain crudeness of evolutionary approach took account merely of the broad stages of outward growth and missed the variety of phenomena that they cover, as well as the significant modern changes inside the street-blocks of already established plan components, notably the traditional ones in town centres. [...]”

“A town plan can be defined, therefore, as the topographical arrangement of an urban built-up area in all its man-made features. It contains three distinct complexes of plan elements:

- streets and their arrangement in a street-system;

- plots and their aggregation in street-blocks; and
- buildings or, more precisely, their block-plans.

The term street here refers to the open space bounded by street-lines and reserved for the use of surface traffic of whatever kind. The arrangement of these contiguous and interdependent spaces within an urban area, when viewed separately from the other elements of the town plan, may be called the street-system.

“The areas within the town plan unoccupied by streets and bounded wholly or in part by street-lines are the street-blocks. Each street-block represents a group of contiguous land parcels or else a single land parcel. Each parcel is essentially a unit of land use; it is physically defined by boundaries on or above ground and may be called a plot, whatever its size. The arrangement of contiguous plots is evident from the plot boundaries and, when considered separately from other elements of the town plan, may be called the plot pattern. [...] A row of plots, placed contiguously along the same street-line, each with its own frontage, forms a plot series.”

Although we agree with Conzen’s schematisation, in our treatment we will prefer to use the definition of “parcel” (or “plot”: the two terms are here employed as synonyms) as a unit of land property, rather than a unit of land use. This is because on the same plot/parcel we could find different land functions.

## 5. Urban Knowledge Units

Caniggia’s urban tissue is structured in elements, structures of elements, systems of structures and organisms of systems. “The moment in which there are several buildings in the same moment in adjoining spaces, a relationship between these buildings has to form: it can be a reciprocally disturbing relationship, the opposite of an efficient relationship or cooperation; in any case, it is a relationship. A relationship always determines a structure, or mutual participation and reciprocal interference between two or more entities. Furthermore, co-presence occurs on two levels: among objects on a similar scale and among objects on a different scale.” [14]

Caniggia and Maffei apply this structure to both buildings and towns, according to the scale of the design: “it is easy to find co-presence on several scales and in the same scale of similar objects or objects containing or contained in a system that necessitates a series of reciprocal behavioral rules and global unity in which objects coexist, triggering off their specific function, correlations and identity.” [14]

At the urban scale, Caniggia identifies specific entities, for instance the lot, which corresponds to Conzen’s plot, the street, the strip, lots facing a route, and the urban tissue, combination of buildings, corresponding to Conzen’s plan unit [after 58].

Karl Kropf in his unpublished PhD thesis [41] proposes to merge Conzen’s plot series and Caniggia’s strip with block and street into the “Textus” (Figure 4). Four levels of Kropf’s hierarchy of built form. “a: Level of resolution is ‘Textus’, level of specificity of one; a1 = plan unit, a2 = shared street/square. b: Level of resolution is ‘Sertum’, level of specificity of one; b1 = block, b2 = street section, b3 = intersection/square. c: Level of resolution is ‘Fines’, level of specificity of two

(plots and blocks); c1 = plot which by extension also functions as a block; c2 = two examples of plot series/pertinent strips – note that a plot series may form part of a block or a block in its own right. d: Level of resolution is ‘Aedes’, level of specificity of three (plots, blocks and buildings); d1 = example of a resultant form (terrace) which occupies an intermediate level between plot and plot series; d2 = example of semi-detached housing – each building crosses a plot boundary, thus is also a resultant form. Footpaths are shown as dashed lines.” [58]

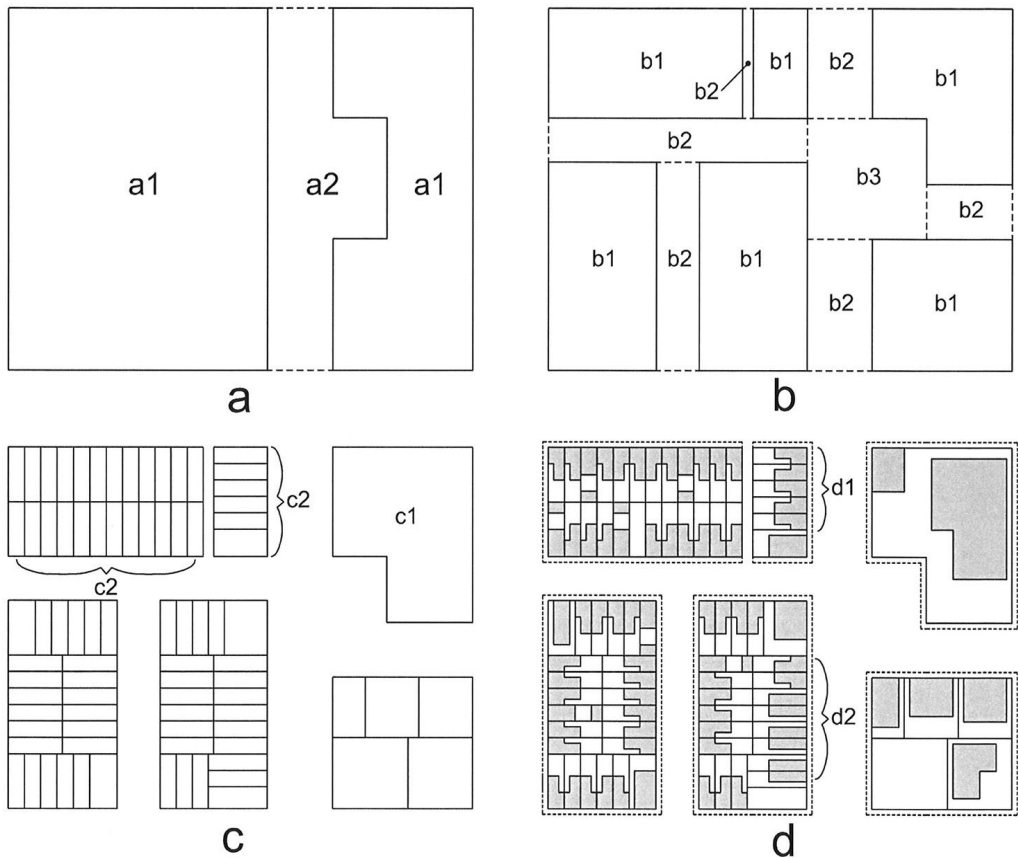


Figure 4. Schematic illustration of four levels of Kropf's hierarchy of built form [41].

A further useful contribution comes from a branch of research which could be described as an “elementarist approach”, practiced in Italy in particular by some exponents of the Venetian and Milanese planning schools [80, 55, 35]. The main idea of this approach about the urban fabric is that the decomposition of the city into new and elemental “urban materials” – which need to be recognised and *named* – could be a way to break with established scientific positions, and to re-think city design.

Through an analysis of the elements of the urban space, Viganò compares different ideal-typical cities, for instance the one of the Rationalists, breaking it down into streets and squares, and suburbs,



composed of enclosures, segregated functions and buildings, large-scale voids, and arteries. These are the ones considered in detail by Venturi, Scott-Brown, and Izenour in *Learning from Las Vegas* [79].

“Viganò harks back to a formal tradition of elementarism in design that was present in the Beaux Arts School, especially in the work of Julien Guadet (*Elements in a Theory of Architecture*, 1902), one of Le Corbusier’s heroes. Elementarism is the isolation of ‘elements’ in a system as discrete objects that maintain constant forms, and the stressing of manipulation of the combinatorial and geometric relationships between such elements.” [65]

## 6. Decomposing the space. Elements and relations

To feed the generative machine of UrbanGen (Urban Generator), we need to define first of all a set of straightforward logic units that can be easily combined to give many different results. The main characteristic of the method we are defining is, in fact, that it is not oriented to the search for a unique solution, according to any optimisation process, but rather the aim is to quickly outline a set of significant alternatives, to support planning, design, and decision-making.

The methodology proceeds to break down the urban fabrics into elemental portions, using the simplest possible terms that still carry meaning relevant to the purposes of the method, i.e. the design of urban places.

Further to Section 5., the elemental portions of urban fabric are termed *urban elements*.

“It is clear that the analysis and decomposition of the urban fabric could proceed ‘downwards’ to the degree of the individual building components: a process which, without logical defects, could lead to the curb, the window, the brick, viewed as elements of higher-level units, which in turn are combined into more and more complex organisms. We decided to impose a ‘downward’ limit, assuming the level of aggregation corresponding to the urban design scale, deriving the data mainly from considerations carried out in parallel on different levels, interwoven with each other:

- the consideration of the analysis schemes explicated in researches quoted in the Section Trial and validation of Urban Morphology Ontology with case-projects;
- the significance of the element according to the scale representation of the outcome of the design process, that is a drawing of urban space;
- the historical meaning and the thematic relevance that the single element has gained in the construction of the city;
- last but not least, the agility of the logic machine that is having to process information.

In particular, the last point introduces the theme of the relations between urban elements. The choice and the enunciation of the elements are in fact due not only to the value of the individual object considered as an independent entity, but above all to the type of relationships that it is able to establish with the other elements of the urban space.” [5]

We refer to this definition of relationship between urban elements, as a *relation*. The *relation* is a both a methodology and a tool to deal with the structure of the city.

## 7. Scaffolding the knowledge

We are advancing both a methodology and a digital tool (the Urban Ontology) for sharing the common understanding of the urban morphology among architects, planners and computers. In the context of information and communication technologies, an ontology defines a set of representational primitives with which to model a domain of knowledge [28].

The word ‘ontology’ has generated in the past a lot of controversy, in particular in discussions about the meaning of the terms’ specification and conceptualisation. A body of formally represented knowledge is based on a conceptualisation: the objects, concepts, and other entities that are assumed to exist in some area of interest and the relationships that hold among them [29]. In particular the word ‘conceptualisation’ has been used to refer to the philosophical reading of the term ontology: a particular system of categories accounting for a certain vision of the world, which does not depend on a particular language [28]. Conceptualisations are immaterial entities that only exist in the mind of the user or a community of users. In order to be documented, communicated and analysed they must be captured, i.e. represented in terms of some concrete artefact. This implies that a language is necessary for representing them in a concise, complete and unambiguous way [30]. In computer science an ontology is an “explicit specification of a conceptualization” [28]. In such an ontology, definitions associate the names of entities in the universe of discourse (e.g., classes, relations, functions, or other objects) with human-readable text describing what the names mean, and formal axioms that constrain the interpretation and well-formed use of these terms. Formally, in computer science an ontology is the statement of a logical theory. The “definition is consistent with the use of formal ontologies in Artificial Intelligence as a way of specifying content-specific agreements for the sharing and reuse of knowledge among software entities and experts. Standard ontology languages should be used to implement ontologies, in order to ensure that the conceptualisation is formally and explicitly encoded. In fact, what is important is what an ontology is for: enabling knowledge sharing and reuse.” [26]

“Conceptualizations are often tacit. They are often not thematised in a systematic way. But tools can be developed to specify and to clarify the concepts involved and to establish their logical structure, and thus to render explicit the underlying taxonomy” [67]. Coherently with this definition, a formal ontology for urban design should be a specification of the urban design conceptualisation. The main problem is that in the domain of urban design a formal conceptualisation (according to Smith’s definition [67]) does not exist.

The Urban Ontology comprises human – and machine – interpretable definitions of the basic elements in the urban fabric and the relations among them.

We consider it possible not only to recognise some of the elements contributing to giving shape to urban spaces, but also to conceptualise them in description of classes (also defined as concepts), with properties describing their interrelationships and attributes.

The definition of the classes is the focus of most ontologies. Knowledge engineering offers three main possible approaches in defining the classes and in developing the class hierarchy [76, 75, 63]:

The *top-down* development process [68] starts with the definition of the general concepts in the urban morphology domain and subsequent specialisation of the concepts. This process matches Conzen's, Caniggia's, and Kropf's categorisations that start with creating some classes for the general concepts of street, block, plot into a unitary category. These authors categorise the classes in space and time, setting out well-structured trees with subclasses. This approach advances the reuse of ontologies and representation of high-level methodological concepts that can prove promising for both the maintenance and the coherence of the ontologies.

The *bottom-up* approach is inspired by atomism, a tradition that dates back to antiquity. The specification of an object in terms of indivisible units and their interactions constitutes the fullest possible description of the object (descriptive aspect), and allows derivation of all other properties of the object (explanatory aspect) [77].

The *bottom-up* expressing methodology is grounded on the formalisation of the most specific classes, 'the leaves of the hierarchy', proceeding with clustering of the classes into broader concepts. We start by analysing promising case-projects, for example *office blocks* and *roundabouts*. We then create two superclasses for them, respectively public space and commercial building.

The *middle-out* development process is a combination of the top-down and bottom-up approaches. The trade-off solution between the above two is the middle-out approach proposed by Uschold & Gruninger [75]: starting with the most important concepts, and then defining higher-level concepts in terms of these. Thus, the higher-level categories will naturally arise. Furthermore, the most important concepts can be extended by defining the lower-level concepts with finer granularity. This approach relieves the problems existing in a bottom-up approach and those in a top-down approach. After deciding on the required concepts, the developers should choose the most appropriate meanings for terms. They should attempt to reuse the most integral and precise definitions for these terms from existing mature ontological definitions. [86]

Actually, "the *middle-out* approach is probably the nearest to the method we used to compile Urban Morphology Ontology. In the writing of the ontology, we firstly defined – both with the scientific literature reference and the selected best practice analysis support – the more salient classes, for instance Public open spaces or Building classes." [26] Then we both generalised and specialised the superclasses and subclasses appropriately. We might start with a few top-level concepts such as *Volumes*, and a few specific *Architectural typologies*, such as *Semi-detached house*, then relate them to a middle-level concept, for example *Buildings*. Then we may want to write the *Functional families*, e.g. *Dwelling*, *Offices*, *Commercial / shopping*, *Production*, which are the middle-level concepts. Unlike hierarchical structures of concepts, i.e. taxonomies, ontologies can give structure to things with a linked or networked "graph". Multiple things can be related to other things, all in a potentially multi-way series of relationships. The Urban Ontology formalises four types of relationships between class individuals: (1) subclass/superclass, (2) meronymic, (3) pertinence and (4) spatial relationships.

1. Subclass/superclass the structure is defined to represent a hierarchy of levels in urban elements.
2. Meronymy studies part-whole relations from a linguistics and cognitive science perspective [38]. Instances of meronymic relations are: “is component of”, “activity has feature”, “collection has member”, “is place of area”, “is stuff of object”, “is portion of mass”.
3. Pertinence relations are used to express a logical precise relevance, e.g. “the private parking pertinent to the commercial shop”.
4. Spatial relationships are subdivided into qualitative relationships, such as directional, nearness and RCC-8 (Region Connection Calculus) topological relationships, and quantitative relationships such as Cartesian, longitudinal and polar relationships.

## 8. An Ontology of the basic units and their relations

For the formalisation of the urban ontology, Berta et al. [5] recognise four reference classes: “Those classes have been defined trying to catch the hierarchical main levels of urban elements that appear in a urban space project.

- **Root class: Geometrical families.** This class tries to divide the urban space elements starting from their intrinsic dimensional nature: lines (i.e. elements with a standard cross section, developed along a path, like the streets), surfaces (i.e. every public or private open and non-covered space), volumes (i.e. every building over covered open space). This class contains also a primary distinction between the public/private conditions (for the linear elements and the surfaces), and between the closed or open volumes.
- **Subclass 1: Functional families.** In this class of the Urban Ontology there is a distinction among the main functional families of the urban elements, such as *dwelling*, *offices*, *private green* etc.
- **Subclass 2: Architectural typologies.** This class articulates the typological peculiarities of the entities, such as *semi-detached house* or *office block* etc.
- **Subclass 3: Distribution type / internal organisation.** In this last class there are some information about the details of the structural schemes (e.g. single, double or multiple span) or about the internal organisation of the entities. This last class matches with the dimensional features, specified for every single element.

Classes and properties can change over time, depending on the socio-economic circumstances, the construction technologies, the culture and so on. Accordingly, classes can be used in different ways, transformed physically, removed or substituted by contemporary ones.”

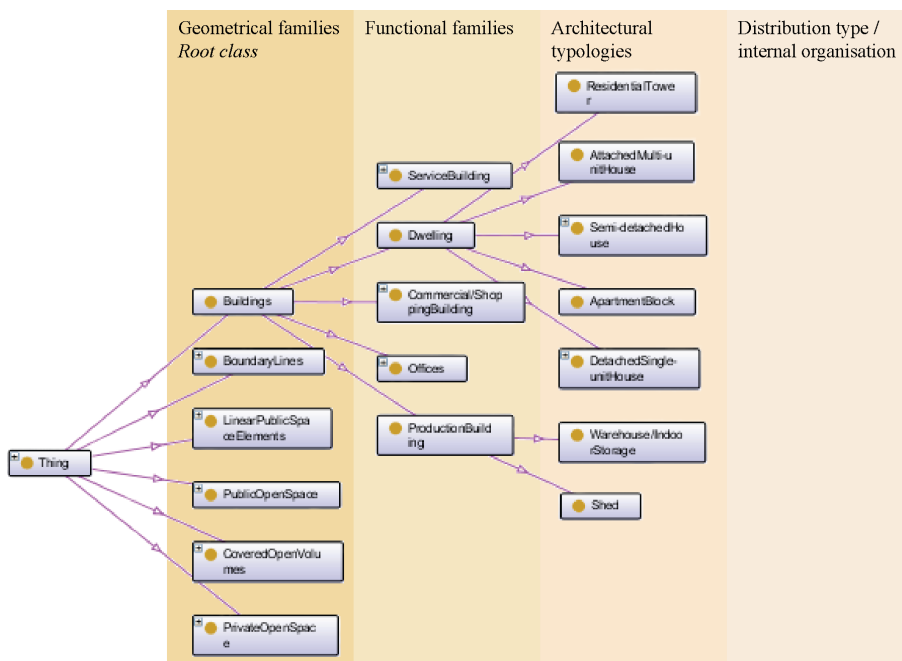


Figure 5. The Root class and the Subclasses for production and dwelling.

### 8.1 Define the properties of classes

“Classes alone will not provide enough information to describe exhaustively the basic elements of the urban fabric. Along with the definition of the classes, their internal structure has to be described by means of their data properties, which includes, for example, the morphological description.” [26]

#### 8.1.1 Morphological description

“The morphological representations are detailed at the level of the individual instances in the ontology.

A unique relationship maps the extension properties (i.e. width, length, height) of the instances in the ontology with the corresponding parameters of virtual geometric models, created as Dynamic Components in SketchUp (Trimble SketchUp, 2014). The models are iconic, for an intuitive recognition of their volume occupancy. Urban typologies have been represented by their minimum bounding box (MBB) specified by six position numerical attributes and 3D attributes. The models have been further typified highlighting especially remarkable elements, e.g. sheds in industrial buildings or structural portals in commercial ones. The purpose is twofold:

- to make the functions and destinations of the instances readily apparent;
- to emphasise the scanning of the space, by analogy with a grid.” [29]

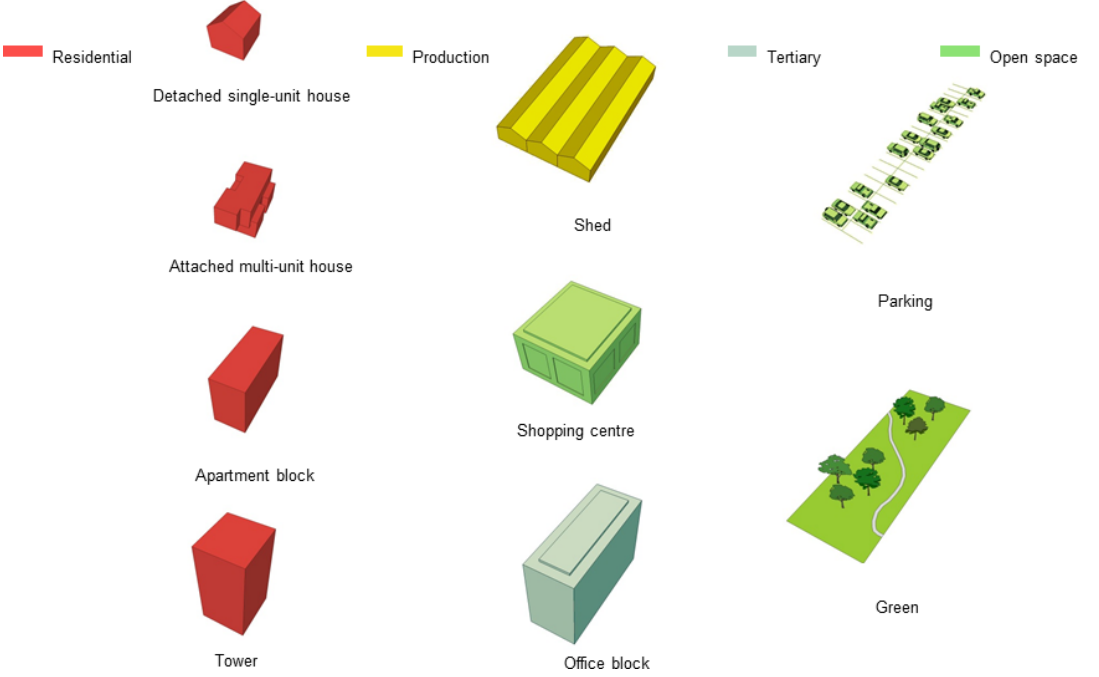


Figure 6. Iconic representations of some instances of the classes.

#### 8.1.2 Connection and Nearness

Region Connection Calculus (RCC8) [62] formalises the topological relationships, for expressing the qualitative spatial relations between building components and urban entities in the Ontology.

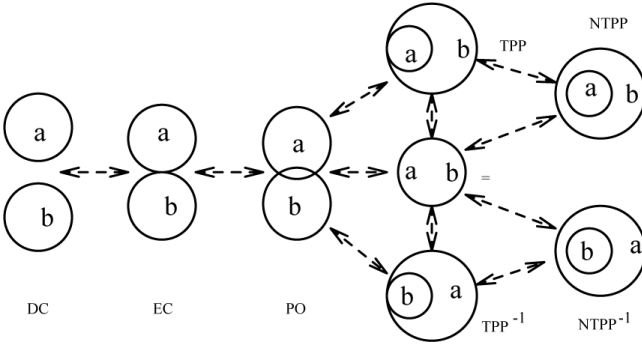


Figure 7. A pictorial representation of the RCC8 relations and their direct topological transitions (after [62]).

*External Connection (EC)* [32]: Two regions are said to be externally connected if they only share borders and thus both regions are connected but are not overlapping. E.g. all the *commercial/shopping volumes* are externally connected with their pertinent *delivery/loading area* (for the definitions of the elements, cf. Figure 5 root class and subclasses).

*Tangential proper part (TPP)*: The tangential proper part relation indicates that one region is a subset of another region and that they share some points on the borders, so the tangential proper part relation is basically a proper part relation where bordering points are shared; e.g. a *delivery/loading area* has a TPP relationship with a *private open space*, or an *on-street parking* has a TPP relationship with a *linear public space element*.

*Contains tangentially (TPPi)*: is the inverse relation of *TPP relation*.

*Non-tangential proper part (NTPP)*: The non-tangential proper part relation is almost similar to the *TPP* relation, differing in the fact that no bordering points are shared; e.g. in a *template* a *shed* could have a NTPP relationship with a *private open space*.

*Contains (NTPPi)*: is the inverse relation of *NTPP relation*.

*Equal to (EQ)*: Two regions, say R1 and R2, are equal if and only if they are exactly the same or, in other words, identical; e.g. the floorplan of a commercial unit has an EQ relationship with the superimposed dwelling floorplan.

*Partially overlaps (PO)*: It is possible for regions to share interior points. When more points than just border points, but not all points of the regions are shared, one can say the regions are partially overlapping; e.g. a *parking canopy* can partially overlap a *private parking*.

*Disconnected (DC)*: If regions R1 and R2 are disconnected, no points exist that are in regions R1 and R2 at the same time and thus the intersection of R1 and R2 is empty; e.g. an *out of-town-main road* has always a DC relationship with a *dwelling building*.

RCC8 provides a powerful and versatile formalism, to represent qualitative spatial relations between building components and urban entities. In particular, the formal semantics of these relations can be described by using propositional logics rather than first-order logics. Accordingly, “reasoning over the RCC-8 relations is decidable [3, 4]. However, RCC does not account for different degrees of proximity or nearness (e.g. A is close to B, X is very far from Y), because discreteness (disconnection) cannot be graded [9]. In order to represent closeness and farness constraints, we introduced maximum and minimum distance values as numeric properties of urban entities pairs. This could be useful in describing the properties of some entities whose presence or absence is not determined in absolute, but only within a given distance from another object. This condition corresponds to the two opposite concepts of: “buffer zone” (or “clear zone”), and “area of influence”. For instance, some special entities, like main infrastructures (such as the motorways), cemeteries, power stations etc. generally require a clear zone around them; other special public functions, such as schools have an influence area, which means that another similar function cannot be placed within a fixed distance; finally, other service functions, such as public parking, need instead to be placed sufficiently near to the functions they serve.” [26]

For the analysis of the urban spatial structure, Kruger [42, 43] uses topological relationships. His aim is the analysis and representation of the relations between adjacency and connectivity measures, qualifiers of the urban spatial structure.

Kruger expresses the interconnections among buildings over plots with graph-theoretic formalisations. “Buildings are represented by points called built forms; external walls and partitions (party walls between buildings) by lines. The connected subgraphs made up of built forms and partitions are called arrays of built forms. This constitutes a simplified view of the built-form subsystem which, together with the channel network, gives rise to an urban graph” [42] (Figure 8, Figure 9).

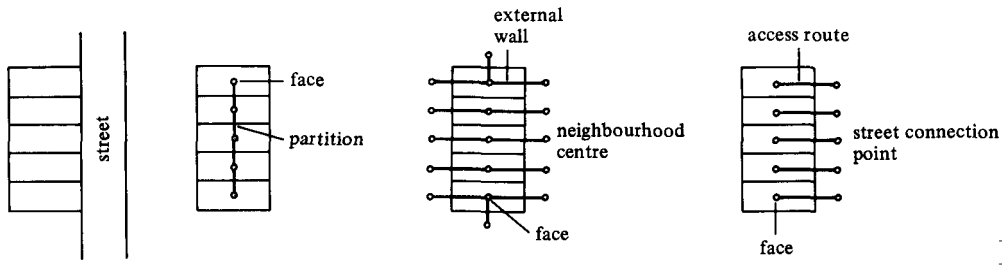


Figure 8. Formalisation of a built-form array in Kruger [42].

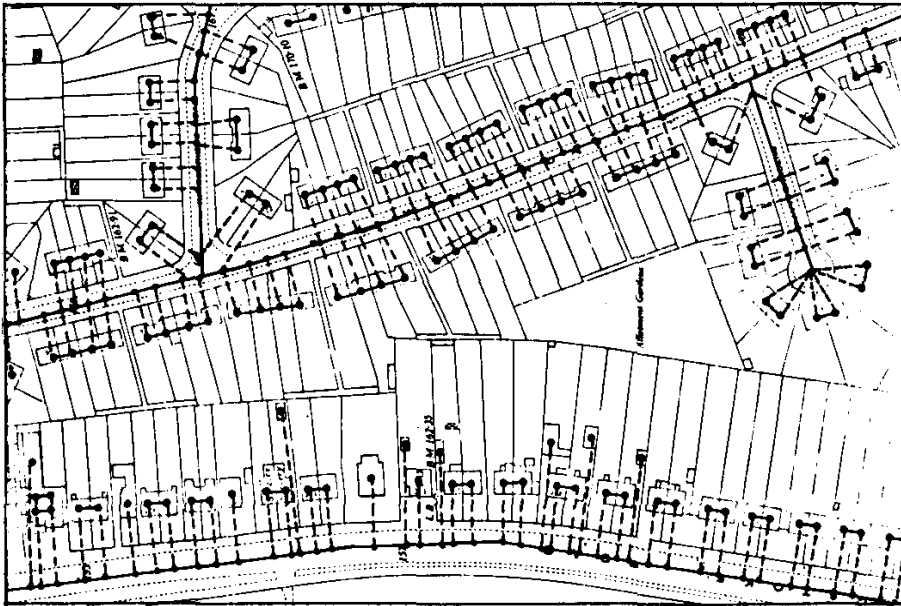


Figure 9. The plans for a residential area of Reading [42].

## 9. Making explicit the assumptions in the domain

In Artificial Intelligence, ontologies are designed with the aim of knowledge disambiguation and sharing. Our ontology of the basic elements in the urban fabric intends to contribute to effectively communicating the intended meaning of the urban units with:



- complete definitions, which are structured in predicates, defined by both necessary and sufficient conditions;
- partial definitions that are defined by either only necessary or only sufficient conditions.

An always *necessary* condition for membership to a class is, for instance, that a member of *Office block*, e.g. *Double-span block*, belongs to the superclass of *Buildings* (parent or ancestor class).

A condition is *sufficient* to determine that something satisfying these conditions is a member of a class. The membership of an instance to a specific class is always a sufficient condition for belonging to its relative superclasses and a necessary condition for belonging to its subclasses. For instance, a sufficient condition for an instance to belong to the “building” class is that it is a tower. The necessary condition for an instance to belong to the “tower” class is that it is a building.

The ontology provides the basis for knowledge representation, contributing to defining the semantic categories that are involved in recognising a fabric peculiar to one or more (portion of) cities. For this use, the ontology supports the urban analysis for design-planning purposes and for descriptive aims. The formal structure of classes, subclasses, and their properties, documented along with textual and diagrammatic descriptions contribute to the clarity of papers, reports, and books [73, 11].

Besides, the ontology provides the knowledge-base to the system, UrbanGen, generating urban fabrics that, to a certain extent, are homologous to the tissue analysed and formalised. UrbanGen infers from the knowledge of morphologies and of adjacencies qualitative spatial representation and reasoning. The system performs complex sequences of inferences to generate the rules of composition for a tissue in a given urban area.

### 9.1. Separating the domain knowledge from its operative use

Artificial intelligence has developed ontologies as effective tools for separating the knowledge in a domain from its uses. For example, an energy simulation program can be defined independently from its uses in any specific architectural or urban design. In principle, the same software can be used to simulate a vehicle.

The separation between the knowledge base construction and its possible practical uses is important because – as we considered in the introduction – the knowledge about urban space morphology and its relationship to building typologies depends primarily on the efforts made by the scientific community over many decades, trying to optimise them in a new formalisation. So, the Knowledge base of the UrbanGen is oriented neither solely toward the design processes, nor solely toward existing city analysis or decision-making etc.; it is instead a more general instrument, whose possible uses can change from time to time and from one user to another.

UrbanGen advances an innovative generative paradigm. This links with the knowledge of elementary urban objects to the knowledge of spatial relations in a domain, to give rise to the process of generating the urban fabrics. Fabrics plural, because this methodology is not designed to give a single answer, and produces a plurality of morphologies, all compliant with the knowledge within the ontological formalisation. This plurality gives greater flexibility to users in defining and

matching their requirements, and to architects and planners to explore a wider range of hypotheses in the view of a greater control over variety and choice.

## 10. UrbanGen

### 10.1 Methodology

In order to highlight the potential of the method used, and to verify the correctness of the determination of unity of knowledge, we set up the inverse exercise of the construction of the urban fabric through the use of the UrbanGen.

So, we consider some actually existing urban fabric (shown and described with photos and short texts), and deconstruct them, reducing them to individual urban elements and relationships that bind them: the urban fabric is put on the anatomy table and dissected into its parts.

At this point, we are able to represent an existing case by means of a diagram, which holds together the elements and relationships that constitute it.

This exercise of breaking down and re-representation is a kind of “litmus test” of the method adopted by the UrbanGen.

The next step is to operate on the diagram, by varying some urban elements or relationships, and verifying such new urban fabric such as is generated; at this point of the process, the stage of verification of the methodology and the stage of design overlap.

### 10.2 Six-tiers generative architecture

UrbanGen generates the fabric for an area through a six-tiers process, along various interactions of the clients, the architects-planners, with the system (Figure 10):

1. Clients’ requirements with questionnaires (online); Architect: masterplan of primary roads and squares (SketchUp).
2. UrbanGen: block layout in the architect’s defined super-blocks; Architect: modifies locally the layout.

**Algorithm:** Convex Optimisation has been implemented in order to generate a tessellation representing the block layout in each super-block. Our approach generalises a methodology adopted for fixed outline floor planning in nanometer integrated circuit technology [66], also taking into account adjacency constraints between blocks/streets and road axes distance constraints, in addition to block shape, dimensions and area constraints. The arrangement of blocks is done in two phases: in the first one blocks are sized and distributed on the surface based on adjacency constraints; in the second one blocks are shaped and positioned on the layout surface, in a such a fashion that no two blocks are overlapping and the minimal distance constraint between road axes is satisfied. We have used an approach based on the Discrete Cauchy-Green transform [84] in order to obtain a solution also for non-rectangular layouts.

3. UrbanGen: plot layout within the blocks; Architect: modifies locally the layout iteratively.

**Algorithm:** Convex Optimisation has been applied to generate the plot layout in each block too. This problem presents a further constraint, i.e. the adjacency of each plot to a street. On the other hand, the minimal distance constraint between road axes is not present.

4. Architect: assigns the templates.
5. UrbanGen: develops the templates.
6. UrbanGen: simulations.

## 11. Urban templates

One of the most common meanings of the word “template”, since the 17<sup>th</sup> Century, is “a gauge, pattern, or mold [...] used as a guide to the form of a piece being made” [15]. The term is probably derived from the French *templet* (i.e. “little temple”, but also used to indicate the weaver’s stretcher), and it means therefore – more generally – a tool, whose purpose is to make easier a particular shaping process.

In the computing nomenclature, the term “template” has gained the meaning of “a preset format for a document or file” [15], a general framework or a base structure to scaffold a customisable document or file.

“In the building process of the knowledge about urban space we used the template concept as a primary tool to describe the different kinds of urban environments that could be shaped by means of UrbanGen software. The whole corpus of single fundamental elements of the urban space (the taxonomy), together with their mutual relations, describes in fact UMO [Urban Morphology Ontology], which could be seen as an ideal all-encompassing repository of any possible configuration of the urban environment, built with the unique condition of respecting the internal rules of the ontology itself. However, this is not actually sufficient – in these terms – to produce a really useful device to support the preliminary urban design [...].

“First of all, because this knowledge base [Figure 11] – containing all the combination possibilities of any public and private buildings and open spaces – includes in itself neither any evaluation of the quality of the generated urban environment, nor any ‘strategic value’ (Hillier, 1996) of the urban space, nor – better – any particular architectural idea or cultural slant about the urban space.

“In other words, a straightforward object-relation based ontology – whose uses were aimed merely at the whole corpus of single entities and their mutual relations – would almost certainly not be sufficient to capture the complexity of a real urban street, whose actual character is defined not only by the presence (or the absence) of a smaller or greater number of singular objects, individually related with other ones, but – most of all – by the existence of some compositions of them seen as a whole from a cultural and historical point of view, which are the only meaningful combinations among the thousands of possible results.” [5]

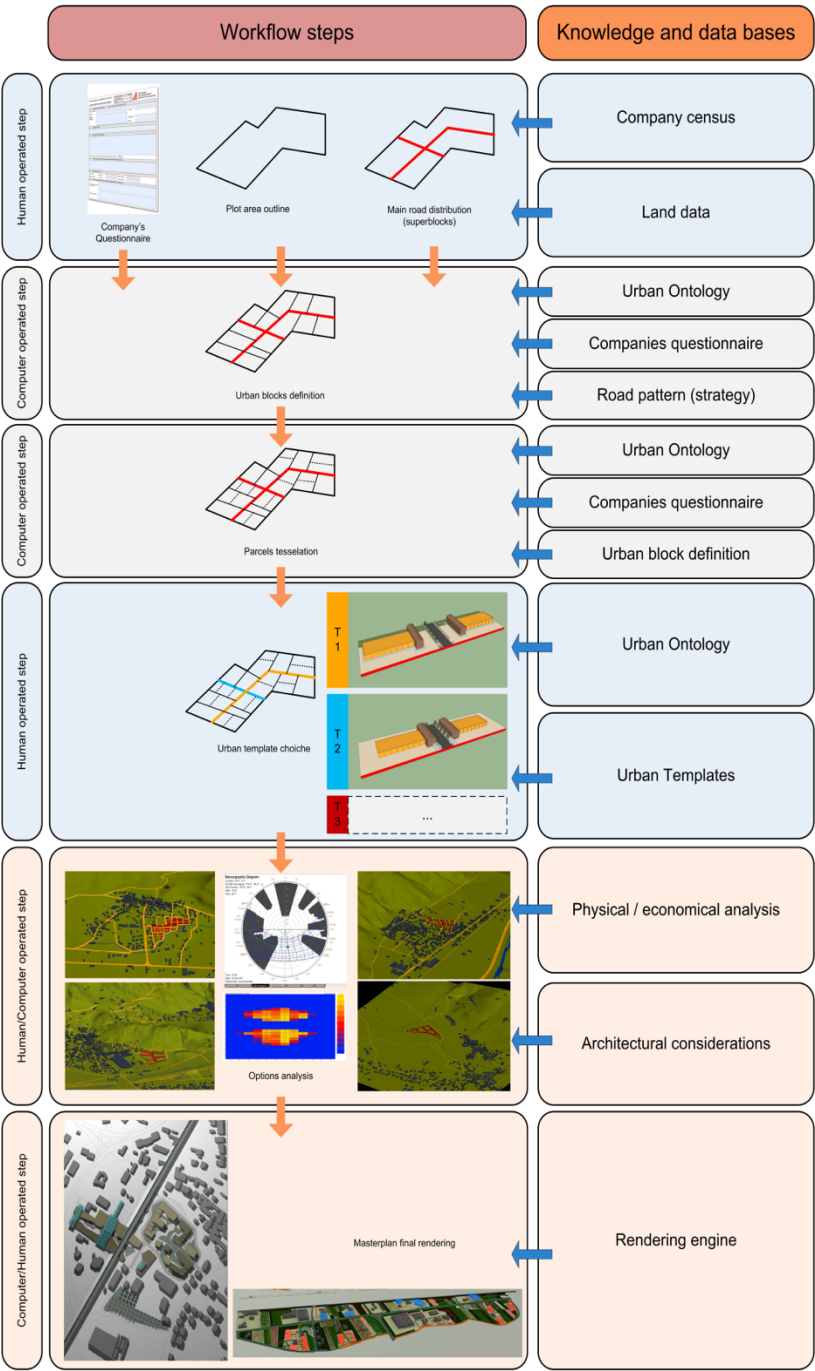


Figure 10. Six-tiers architecture: a simplified workflow diagram of UrbanGen.

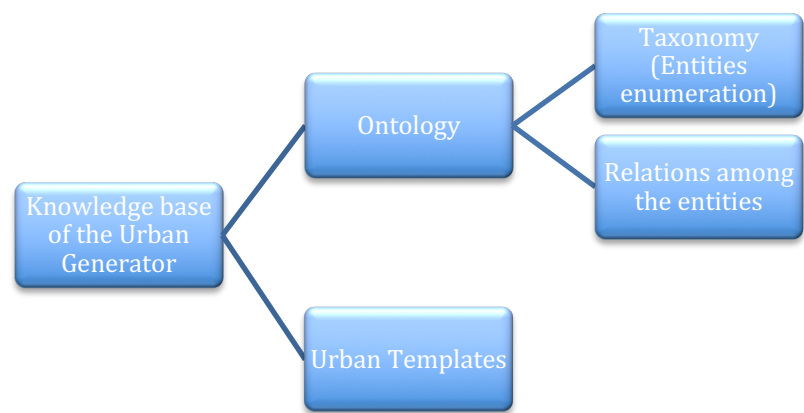


Figure 11. A scheme of the UrbanGen’s Knowledge base (after [5]).

The regularities, or ‘habitual’, generic processes, have been identified by examining and comparing many examples. Probably the most fundamental generic process is the formation of routes and the occupation of the land made accessible on either side of the route [14, 49], coherently with the middle-out methodology. A further step in the process is the extension outward and progressive connection of further routes and occupation of land to create the complementary pattern of a contiguous route network and isolated street blocks [14].

The difference between an Ontology with simple object-relations, see left part of Figure 12, and the relations according to the Urban Templates, see right part of Figure 12.

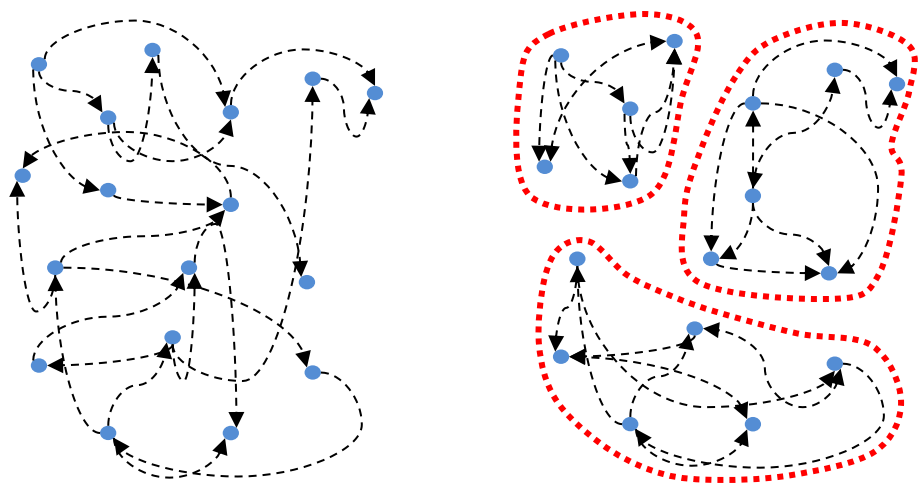


Figure 12. Ontology formalisation of straightforward object-relation (left), the relations according to the Urban Templates (right).

## 12. Six-tiers generative process trialled in a case-project

The Municipality of Collegno commissioned our Lab to undertake the study in order to gain an understanding of design alternatives for a new eco-industrial park (EIP) on the Northern fringe of Turin, Italy. The area for the development is about 50 ha, and nearly 100 companies had expressed interest in settling in.

The public stakeholder aims to preserve land use, protect environment, and develop economic policies to foster innovative economic models and organisation by means of activities in planning, design, construction and operation of the industrial development.

In the EIP area, the layouts of plots and buildings has to achieve a number of objectives:

- incremental development model for the settling of the activities in the park over a decade;
- industrial requirements evolving in time, during the development;
- layout for the new park fitting the dynamic requirements;
- layout of entrepreneurial activities within the EIP boundaries;
- shape the volumes of the industrial activities and the exchanges among them in 3D to reduce plant and infrastructures footprint.

*UrbanGen* was trialled for interactively generating the fabric for the EIP. To ease the interaction with the generative system, the system was implemented on top of SketchUp that provides the drawing and visualisation functions to the users.

The six-tiers generative architecture, applied to the case-project, went through the following process:

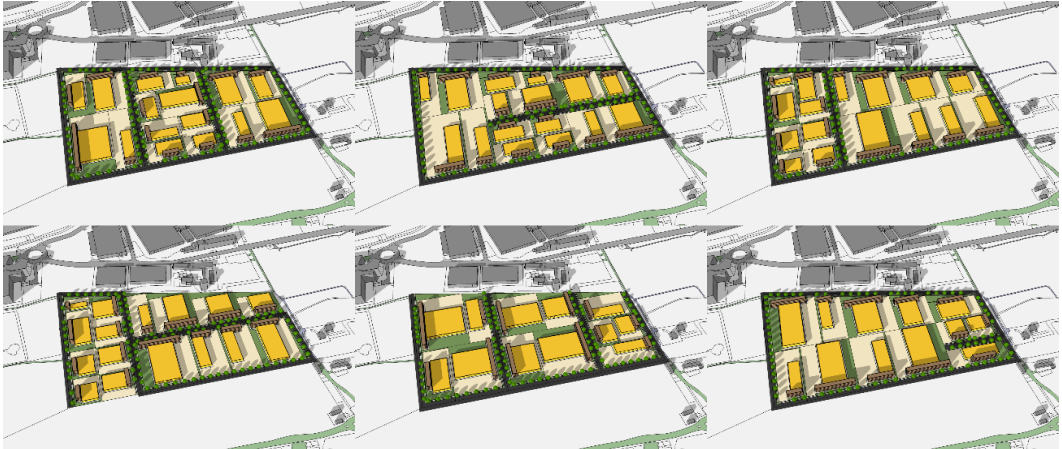
1. The public stakeholder's requirements were defined with interviews and questionnaires. The architect-planner outlined a masterplan of the primary roads and the squares (in SketchUp). The industries interested in settling in the new EIP were interviewed to assess their main requirements, i.e. activities factsheet, area covered in the present and in future plans, products and by-products, waste, logistics, water and energy demands. The methodology implemented in the J-Park Simulator [88], has been used to translate the industrial requirements into topological constraints, i.e. adjacency constraints, etc. J-Park Simulator is a platform for establishing cross domain correlations in resource and energy management of eco-industrial parks. It uses a knowledge graph to store and link information semantically. To allow for a high degree of knowledge reusability, many classes and relations in J-Park Simulator are defined and bundled in modular ontologies, based on OntoCAPE [88, 89], which is a large-scale ontology for the domain of Computer Aided Process Engineering.
2. The resulting clusters influence the layout of the industrial activities within the park. In this way a subset of the Convex Optimisation constraints is defined, i.e. the following input constraints:
  - a) Block layout and its area;

- b) Area of the plots (minimum and maximum values allowed);
  - c) Adjacency conditions between pair of plots;
  - d) Position of plots inside the block: top, bottom, left, right (the presence of both the top and the left condition will indicate the top-left corner and so on);
  - e) Maximum and minimum ratio between the horizontal and the vertical dimension of each plot;
  - f) Minimum distance between road axes;
3. The user draws / imports the superblock (a superblock is a connected surface delimited by primary roads) in SketchUp with land data, topography, existing road system, connections to the surroundings. We have not fully implemented Conzen's first complex of town elements, namely streets and their arrangement in a street-system, since UrbanGen starts generating streets at the "superblock scale" (i.e. the first level of Kropf's hierarchy), leaving the street design for upper scales to the designer's touch.
  4. Plots and their aggregation in street-blocks, which are Conzen's second complex of town elements, are generated together with the street-system inside the super-block: this is equivalent to the upper three levels of Kropf's hierarchy, but we don't generate them in same order. In this step the architect modifies locally the layout iteratively, interacting with UrbanGen system, according to the desired goals (e.g., for the EIP application field, synergies, access to infrastructures, services, existing road system, etc.), without a clear order between plot and street generation being defined (see paragraph 8.2.1).
  5. The plot/road layout is exported back in SketchUp.
  6. The architect assigns a template to each plot. The templates are generated by UrbanGen software (see paragraph 8.2.2). The user can customize each Urban Template generated by the software for a plot, via a dialog box, and can start the simulations and the renderings. This step is not equivalent to Conzen's third complex of town elements (cf. 2.2), i.e. "buildings or, more precisely, their block-plans." In fact, our definition of Urban Template holds together the built (private) and unbuilt (private and public) space. Compared with the fourth level of Kropf's hierarchy, our definition of Urban Template also considers the roadway (public space), so in our case until Kropf's step c) the streets have no thickness; then they take one as defined by the specific template.
  7. The user can get back to the Template/s to configure and customise them, for instance to accommodate changing companies' requests. The generative process can resume from point 1., 2. or 3.

### 13. Design is not an optimisation process

Christopher Alexander in "A City Is Not a Tree" has described cities as complex phenomena, and the paradigms which we use for conceptualising, planning and designing them, as having a deep influence and being "enormously consequential" [51].

In the EIP case-project, the aim of UrbanGen is to provide stakeholders and decision-makers with an insight about layouts, matching their requirements and objectives (Figure 13). Despite the relative smallness of the area and the given set of actors, the generative process can raise an extremely large number of compliant layouts.



*Figure 13. UrbanGen generates and visualises a number of alternative layouts, matching the given requirements and the options. A plurality of design scenarios for a new eco-industrial park in Collegno.*

Three leading approaches are envisaged [34, 8, 10]:

*Optimisation:* all the solutions are analysed, to find the solution that best matches the given goals and the requirements. We consider this approach unsatisfactory, because the outcome is a single result and directly relates to the consistency of the hypothesis that is often not so stable or well-defined. Thus, it is valid in that it gives a high chance of achieving an optimal result, under the specific circumstances, but infeasible or unsatisfactory in a slightly different or changing context.

*Interactivity:* during the generation of the solutions. The user is requested to put in order of preference or, at least, to express her/his approval or disapproval of the solutions generated, so that the search algorithm can address the exploration toward promising areas of the ‘design space’. The process repeats until the user evaluates the solution as satisfactory. This methodology for pruning the exploration of the full space of the solutions assumes that despite the streamlining in the generation of the solution it can lead to solution/s that are valued as satisfactory. Conversely, “the incorporation of expert knowledge, intuition and experience can compensate for the unavoidable simplifications induced by the model” [10].

*Exploration:* the overall space of the solutions is generated and is presented to the participants so that they can gain an understanding of the solution space. The challenge is to provide an overview of an enormous variety of layouts with small variations that are hardly to be perceived and appreciated. The large plurality of layouts can easily turn cumbersome or boring in a real planning and decision-making process.



Exploration relies on the effective capability to provide a synthetic view on the ‘design space’. The phrase ‘design space’ is used to mean the set of all the layouts consistent with the given generative hypotheses: “Modern design theory views the design process as a search in a predefined space for possible designs” [27].

For empowering users to explore the multidimensional design space defined by one or more Urban templates, we have developed a specific implementation parallel coordinates plot [36]: each variable is represented as a vertical axis with the ranges of values increasing from the bottom of the axis to the top. Several axes can be accommodated in parallel, the data are plotted on these axes; hence the name “parallel coordinates”. The corresponding points are connected with polylines. Each polyline represents a single data dimension, and lines crossing between dimensions often indicate inverse correlation. A specific advantage of parallel coordinates is that they are relatively compact, so several variables can be analysed simultaneously.

A single design solution is represented as one polyline whose vertices intersect the parallel axes: each intersection point identifies the value of the corresponding variable. To analyse the large multidimensional design space generated, many axes can be placed alongside easily.

### 13.1 Interactivity in exploration

To enable the analysis of large design spaces, we have implemented interaction techniques with parallel coordinates to enhance users’ direct exploration.

**Selection of a design solution**, the user can move the mouse over a polyline to highlight it and to visualise the corresponding design solution, represented with its plan and its isometric view in two windows at bottom-left corner of Figure 14.

**Multiple selection**, holding down the left mouse button and moving the cursor over various polylines allows the user to select a subset of design solutions. The selected set of polylines can be used as input for subsequent operations, such as further selections, e.g. on different axes, or for the masking or isolation of solutions.

**Animation**, moving the mouse across several polylines animates the design solutions, visualised in two bottom-left windows. The user can control the speed of the animation with the movement of the cursor.

For example, let’s imagine an architect considering the layout for a plot: the user knows the dimensions of the plot, the gross floor area, and may have in mind an approximate length of the front of the building. In the parallel coordinates plot, each requirement or commitment turns into a multiple selection action over the corresponding variables. The selection process highlights a subset of design solutions, that the system represents assigning a specific colour to the selected polylines (Figure 10). Moving the cursor over this subset, the user can analyse the single design solutions and the values of their variables over the axes. Alternatively, the user can interactively animate the selected subset, moving the cursor vertically over an axis. For instance, sliding the mouse over the axis representing the dimension of the front, the plan and isometric views rapidly represent the different solutions that, as in a flip book, turn into the animation of the layouts with the front size of the building changing.

## 14. Discussion

The planning and design of EIP has offered an effective case for trialling UrbanGen, because of the not so large number of stakeholders and decision-makers involved, and the structured domain offered by the industrial activities and their management, especially with a view to achieving environmental sustainability by synergies in the park.

By and large, UrbanGen's ontologies have proved a methodology to capture and represent the knowledge arising from the questionnaires and the interviews (cf. 11.2). Ontology engineering was successfully used to highlight inconsistencies in the users' knowledge, for instance conflicting objectives or requirements. To manage these inconsistencies, in certain cases the recoding of the knowledge has proved feasible, in other cases the users were required to reconsider them. Is the consistency of the knowledge a positive requirement for planning and design? Or does it turn into a constraint for the practical use in real projects? The current implementation of UrbanGen pursues coherence within the knowledge within what is considered as the unitary element of design, namely the individual industrial activity that fits within a plot. For example, the requirements for a warehouse should be consistent within the activity. If the ontology highlights an inconsistency, it has to be addressed and fixed. Conversely, different activities can have unmatched objectives and requirements, thus they can end up diverging.

For the generation of the layouts in the EIP, UrbanGen applies the urban ontology (cf. 8.) that addresses the generation of urban tissues in general, unspecific to any case and city, more precisely not conceived expressly for the generation of industrial parks. Despite the general assumption in the generative

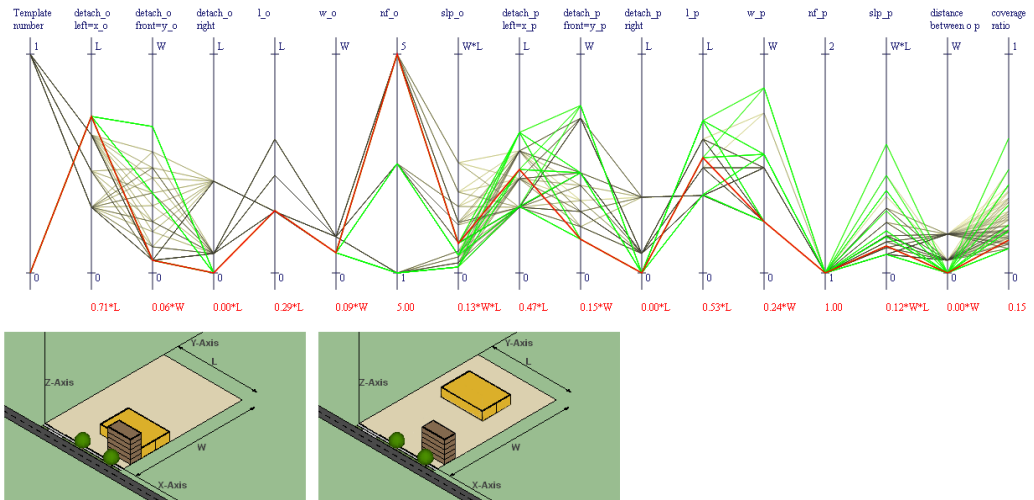


Figure 14. Interactive Parallel Coordinates for the layout of a rectangular plot. Two different Urban templates are considered: Template 0 - the office building and the shed are externally connected and both semi-detached; Template 1 - the office building and the shed are disconnected

*and both detached. Selecting a polyline in the parallel coordinates plot displays the corresponding solution in a window. Several windows-solutions can be accommodated side-to-side.*

knowledge, the layout of the building within the plot and the arrangement of all the plots in the EIP has proved convincing; the system avoids over simplification, i.e. ‘blocky’ shapes, instead it is able to shape building and plots matching the users’ requirements with buildings rationally using the target surface. It also avoids oversimplifying or over-reducing the footprints, even though industrial buildings have the predisposition to repetition and modularity for the sake of open plan, inner accessibility, and construction techs.

The managers of EIP have appreciated UrbanGen’s capability to overcome the tendency of most ‘human’ planners when shaping parks to reduce the peculiarities of each activity hosted into surface covered and front span on the main access roads [24, 50]. This tends to produce repetitive and regular layouts for each plot and their repetition along streets. UrbanGen manages each activity individually and tries to match its own requirements into the plot. In the tessellation of plots, rectangular ones are one option in the much wider geometrical capabilities offered because of the rational allocation and use of available space. Moreover, the system never gets tired or bored, thus both small and major changes requested are addressed.

For the aim of use in real projects, the approach towards the generation of the full ‘design space’ (cf. 13.) has been considered counterintuitive by the managers, because of their practice with designers that tend to produce a synthesis into few or just one proposal.

The parallel coordinates tool has required the user to spend time to get effective in using it, although interaction with it has often been indirect, mediated by a facilitator.

The use of parallel coordinates to explore and interact with the design space, as far as we know, has not been tested systematically [10, 13, 20, 25, 6], with a usability testing methodology. We did not do so in this case-project, while a methodological-grounded assessment is envisaged for a next trial of UrbanGen.

During the EIP trial, the main drawback encountered relates to the users’ access to an extensive set of variables outlining nearly all the variability in the layout of a plot (Figure 14), i.e. (1) the destination of the building, detach of the building from the plot (2) left border, (3) front border, and (4) right border, dimension of the building along the (5) x axis and (6) y axis, (7) number of floors, (8) gross floor surface, (9) distance between buildings, (10) surface to volume ratio, (11) direct solar irradiance, (12) plot coverage ratio.

The exhaustive representation of the design space has proved to divert the attention of the stakeholders from the decisions to the means of representation. This is an issue common to the analysis of very-large datasets, thus the research in parallel coordinates plotting for problem solving has advanced:

- smart ordering of variables along the axes, depicting pairwise relationships [31];
- prioritising variables according to the users’ objectives, i.e. with most convex Pareto fronts [74];

- emphasizing pattern in the cases by various data properties [25, 31, 23];
- reducing the visualisation of the polylines, e.g. bundling clusters of cases by similarity-based reordering [46, 72].

The clustering of the generated plots, according to users' defined priorities in the variables, has been trialled with different visualisations of polylines, with line thickness and shading of groups. As a result of this trial, we consider the clustering of layouts a method of highlighting typological variations in the generated plots. This variation relates to the generative knowledge embedded in the Urban Templates (cf. 11.) as the knowledge mechanisms that play a role in generating the plot 'character'. Certainly, further research could investigate the knowledge that the designer unconsciously uses in shaping a layout. This body of knowledge pertains to roads, buildings, infrastructures, equipment, areas, networks and so forth. Some properties are common, for instance pertaining to spatial rules and reasoning or to practices, and can be shared with Urban Morphology Ontology: "This conception points directly to what are by now commonly held ideas of good urban design such as clear definition of public and private space, maintaining front-to-front relations of plots across a street and back-to-back relation across a block. Taking the street (highway with plots either side) as the compositional element, as opposed to the block or perimeter block, reinforces the positive principles of urban design more effectively and brings out other issues the perimeter block conception does not raise. The perimeter block idea leaves open the question of the hierarchy, identity and character of the individual streets that serve the different sides of the block - given a position within a network of streets with different character" [41].

Further properties are peculiar to the pilot-project and have to be formalised expressly in the Urban Templates.

We expect this knowledge to develop in time from our work and from other research teams; several compilations set out the advancements in ontology for formalising building or urban knowledge [21, 37, 82]. Scholars value the ontology scaffolding of knowledge, to support sharing among architects, planners, policy-makers, and computers.

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