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Semantic knowledge in generation of 3D layouts for decision-making

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ABSTRACT

Generative computation has the potential to enhance the accuracy, effectiveness, and creativity of spatial layout in design and planning. The paper proposes a methodology to separate the knowledge about objects, spatial relationships, and constraints from the generative process. The separation between the knowledge in a domain and its possible practical uses is an important achievement of semantic technologies, because it grants access to a large body of knowledge, spanning various aspects and processes across buildings and cities, which is being codified into formal ontologies. The present study has reused existing knowledge from two established ontologies. An illustrative case-project demonstrates the suitability of the methodology for a complex layout planning problem, involving a large number of decision-makers, with multiple competing objectives and criteria. The system implements multidimensional visual interactive tools to assist designers, planners, and decision-makers in exploring the layouts and the criteria, to develop their confidence in what qualifies as a good and effective solution.

1. Introduction

The paper presents a system for generating the spatial layout of objects according to knowledge about them and about the constraints and relationships for the design layout.

The knowledge is expressed with semantic technologies, namely formal ontologies. Artificial Intelligence has developed ontologies as effective tools for separating the knowledge in a domain from its uses. The separation between the scaffolding and management of knowledge and its possible practical uses is relevant, because a large body of knowledge, spanning various aspects and processes across buildings and cities, is already being codified into formal ontologies, many of them accessible as open-source. One aim of the present study is reusing a portion of the knowledge in previously created ontologies for layout design. The reuse of the knowledge profits from the efforts made by the scientific community over decades. For the generation and evaluation of layouts, two existing ontologies have been used in the present study. The methodology, developed and tested in the research, for the reuse of existing ontologies allows the easy integration of further formal knowledge.

Enabling semantic technologies have supported the development of the generative system: Web Ontology Language (OWL) for the representation of the formal knowledge, and Semantic Web Rule Language (SWRL) for the expression of rules and logic. The integration of SWRL with OWL has enhanced the reasoning on the knowledge for the generation of the layouts. The reasoning has been used to check the consistency of knowledge about the various constraints on and relationships for the objects, and to infer from the initially implemented knowledge further logical consequences. Furthermore, the semantic inference engine has been able to derive every layout instance compliant with the knowledge in the ontologies. This has a far-reaching applicative consequence: the system can automatically generate all the layouts compliant with the knowledge about the objects, the constraints and the relationships.

An assumption of the research is that the generation of all the compliant layouts gives stakeholders more power to define and match their requirements, and allows designers to explore a wider range of hypotheses with the aim of greater control over variety and choice.

Hou and Stouffs [1] have studied how small quantitative change in the layouts can improve algorithmic design in the satisfaction of adjacency and area constraints. The assumption of the present work is that a small quantitative change in objectives or criteria may produce substantially different layouts that may better match the designers' or stakeholders' expectations. We have set the decision-makers (DMs) at the core of the decision process: the aim is supporting DMs' exploration of solutions to fit their objectives.

Multiobjective decision analysis methods [2–4] provide the theoretical framework: within all the compliant layouts generated at least one set of equally interesting Pareto optimal solutions can be defined. This Pareto set recognises all the layouts for which no criterion can be

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improved except at the expense of at least one of the other criteria. For many real-world projects, the DMs' definition of objectives and criteria is impaired by various uncertainty factors. To add robustness to the decision process, DMs are provided with visual interactive tools to explore the layouts and the criteria, to learn the trade-offs between them. The visual interaction assists the designers and DMs to develop their confidence in what qualifies as a good and effective layout.

2. Overview of semantic technologies and ontologies in AEC and Smart City

Semantic technologies are becoming more and more common in the fields of Architecture, Engineering and Construction (AEC), and of Smart Cities.

A number of enabling technologies have supported the development

Table 1
Ontologies related to AEC and Smart City with the main reference domains implemented [13].

Formal name	Ontology	Reference	Domains: Administrative	AEC	Building	Observations	Public Serv.	Smart City	Transport
AFPS-Onto	Active fall protection system ontology	[18]		■					
ALMANAC platform		[19]				■		■	
BIMSO	BIM shared ontology	[20]		■					
BOnSAI	Building ontology for ambient intelligence	[21]			■	■			
BOT	Building topology ontology	[22]		■	■				
BridgeOnto	Bridge deterioration ontology	[23]		■					■
City ontology		[24]						■	
CityBench		[25]				■		■	
CNC ontology	Construction noise control ontology	[26]		■					
CQIEOntology	Construction quality inspection and evaluation ontology	[27]		■					
Data quality control	Data quality control framework	[28]		■		■		■	
Defect	Defect ontology	[29]		■					
Delay	Delay analysis ontology	[30]		■					
DIMMER	DIMMER systems integration ontology	[31]			■	■		■	
DogOnt	Ontology modelling for intelligent domotic environments	[32]		■		■			
E-society	E-society ontology	[33]		■				■	
fiesta-iot	FIESTA-IoT	[34]				■		■	
FMUont	Functional mock-up ontology	[35]		■	■				
FOWLA		[36]		■					
Freight	Freight data ontology	[37]							■
gci	Global City Indicator Foundation Ontology	[38]	■			■	■	■	
IC-PRO-Onto	Infrastructure and construction process ontology	[39]		■					
ifcOWL	ifcOWL	[40]		■					
INTER-IoT		[41]				■		■	
km4c	Km4city, the DISITKnowledge Model for City and Mobility	[42]	■		■	■	■	■	■
oldssn	The W3C Semantic Sensor Network Ontology	[43]				■		■	
OntoFM	FM ontology	[44]		■	■	■			
Onto-integrator	Ontology integrator	[45]		■					
OptEEmAL		[46]		■				■	
pep	Procedure Execution Ontology	[47]				■		■	
Performance Assessment	Performance Assessment Ontology	[48]		■	■				
PRISMA		[49]						■	
QA-ontology	Quality audit ontology	[50]		■					
RaCoOn	Rail core ontology	[51]		■					
READY4SmartCities		[52]							
san	Semantic Actuator Network	[53]				■		■	
sao	Stream Annotation Ontology	[54]			■	■		■	■
SAREF	Smart appliances reference ontology	[55]			■	■		■	
sco	Sensor Cloud Ontology	[56]				■		■	
sctc	STAR-CITY	[57]				■	■	■	
seas	SEAS	[47]				■		■	
SEMANCO		[58]		■					
Semantic smart gateway	Semantic smart gateway framework	[59]				■			
Sii-mobility		[60]				■			
SIMModel ontology	Simulation domain model	[61]		■	■				
SI-Onto	Social-equity-oriented stakeholder Involvement ontology	[62]	■	■				■	
smart-city	Smart City Ontology	[63]	■			■	■	■	■
sosa	Sensor, Observation, Sample, and Actuator	[64]				■		■	
Spatial planning	Ontology for modelling spatial planning systems	[65]		■				■	
ssn	Semantic Sensor Network Ontology	[66]				■		■	
SSN ontology	Semantic sensor network (SSN) ontology	[67]				■			
ThinkHome	ThinkHome	[68]		■	■				
vital	VITAL	[69]				■	■	■	
Web of things (WoT)		[70]				■		■	

of semantic technologies: Web Ontology Language (OWL) is a set of languages for authoring ontologies for formal knowledge representation; Semantic Web Rule Language (SWRL) is a language to express rules and logic, that combined with OWL, enhances the reasoning on knowledge.

Ontologies in artificial intelligence are “explicit specification of a conceptualization” [5], in which is modelled a domain of knowledge as a set of concepts and the relationships among those concepts. “A domain ontology does not aim to exhaustively list all concepts in a domain, but rather to build an abstract (yet extendable) philosophical (yet practical) conceptualization of the essence of knowledge in a domain.” [6].

For semantic technologies, a body of studies has focused on the major fields of use in interoperability, information representation and extraction, knowledge management, and logical inference and proofs.

2.1. Interoperability

Formal ontologies offer the capacity to integrate, to link data within and across domains, e.g. Architecture, Engineering and Construction (AEC), Smart City, energy, transportation, environment, heritage, …, and from different sources, e.g. BIM, CAD, GIS, sensor data, simulation data, … The common method is to use formal knowledge-based vocabularies, i.e. ontologies, that describe information in a shared machine-readable format [7].

Bittner et al. [8] and Visser et al. [9] distinguish between syntax, structure, and semantic interoperability in data. Syntax and structure interoperability deals with representation, format, model interoperability in data. Semantic interoperability deals with the meanings of data: it sets connections between computers, between things and computers, between humans and computers, and between humans.

Ontologies are formal specifications of shared conceptualisations [10]. As a technology, ontologies have largely been implemented as meaning models to capture conceptualisations for representing and sharing them. As a methodology, ontologies have provided formal methods for clarifying the conceptualisations and the specifications.

Smart City is commonly understood to mean a community of people, resources, infrastructure and environment that can benefit from being interconnected [11,12]. In this regard, ontologies, both as technology and methodology, have been extensively implemented for interoperability among, for instance, data infrastructures, mobile apps, Internet of Things platforms, and a heterogeneous plethora of users. Espinoza-Arias et al. [13] have reviewed the ontologies being developed in Smart City.

The AEC industry have invested in interoperability at the application level, BIM above all, and at inter-application scale, e.g. across CAD and GIS systems, and towards ICT technologies, e.g. digital twin, internet of things, and big data. Espinoza-Arias et al. [13] and Costin and Eastman [7] wide-scoping surveys of ontologies are listed in **Table 1**. The Table summarises the reference domains for the ontologies: (1) **AEC** umbrella refers to entities, properties, and functionalities for design, analysis, production, and maintenance of building facilities; (2) **Building** domain represents all objects or functions contained in or related to an edifice; (3) **Administrative Area** domain represents places delineated for jurisdiction purposes of a particular government (e.g., city, district, neighbourhood, etc.); (4) **Public Service** domain involves all services provided by public administrations and organisations (e.g., waste management, public parking, water quality control, etc.); (5) **Observations/IoT** domain represents all measured values related to a particular property of any feature of interest (e.g., noise levels, weather conditions, air quality, etc.); (6) **Smart City** umbrella refers to a city managing, in an intelligent way, all its associated resources to improve the quality of life and to enhance the quality of the services to citizens; and (7) **Transport** describes activities performed in a city relevant to moving means or service.

2.2. Information representation and extraction

Ontologies have been developed to extract and represent information from unstructured data, e.g. from different textual construction documents [14], from images, or from remote sensing which is a vivid research topic, beyond the aims of the present paper. Semantic-based data mining can discover regularities and patterns, which can lead to informed design or planning actions [15]. An emerging field is information representation and extraction from big data generated by the operation of robots and unmanned vehicles, for instance from vacuum cleaning robots. Ontologies provide the knowledge to the robot for mapping rooms and objects, for delivery of daily robotic services [16], and for extracting, validating, correcting and generating descriptive profiles out of datasets without prior knowledge [17].

2.3. Knowledge management

Gruber’s foundational definition of a formal ontology, “explicit specification of a conceptualization” [5], has advanced the management of knowledge as a set of concepts and their relationships within a domain that is a set of representational primitives with which to model a discourse or a knowledge domain. That definition is compatible with the implementation of ontologies for the management, sharing, and reuse of knowledge. “Shared use means that the ontology describes general knowledge rather than a personal one. This property implies that the ontology represents a knowledge base valid for a context or accepted by a group or a community, who could possibly reuse and adapt it for diverse purposes.” [71].

At the city scale, a large body of applications have been developed since the pioneering work of Fonseca et al. [72], grounded on reusing existing knowledge from previous urban GIS projects with the creation of software components from diverse ontologies as a matter of sharing knowledge and data.

Daneshfar et al. [73] have built the *GISOntology4Renovation* ontology to formalise the knowledge about the surrounding environment of a building in an urban context. The ontology makes explicit the conceptualisation about objects and processes in building renovation. The aim is to “to create a knowledge management system for different experts involved in the process of the building renovation, to extend the information and stretch the domain from the individual building to the environment.” They have acquired the domain knowledge from literature and renovation pilot-projects.

In Ardissono et al. [74] the *Ontomap* ontology makes explicit the users’ conceptualisation about community maps, the individual’s information that enriches the interaction with maps during participatory decision-making. The system interprets the individual’s vocabulary, from lexis, occurring during queries-interactions, and applies semantic interpretation and disambiguation based on the context. The system is able to identify relevant concepts and to proactively suggest pertinent knowledge with interaction in natural language.

Sun et al. [75] have managed the knowledge in the domain of urban master planning in mountain areas. They have developed an augmented planning support system for efficient and flexible decision making, whose domain knowledge is provided by an urban planning ontology.

The ontology manages domain knowledge in master planning for mountain zones. The ontology has been structured into three top-levels, respectively domain, task, and application in urban planning.

The domain level encompasses the specific lexicon of urban planning. A further conceptualisation is given by urban physical layers, i.e. land use, building, network, landscaping, and intangible ones, i.e. social, economic, cultural, environmental, administrative. There are ten root classes: City Size, Urban System Urban Master Layout, Historic City Protection, Spatial Control, Immediate Plan, Urban Functional, Urban Ecological Protection, Basic Materials, and Development Strategy. The classes have subclasses, through “is a” relationships.

The task level manages the knowledge relevant to the urban planning workflow, i.e. filling, approval, implementation, management, and supervision, to the planning tasks, e.g. master planning, detailed planning, construction planning, and so on, and to the approval process.

The augmented planning support system framework, based on domain knowledge, facilitates various urban actors to reach an informed consensus, grounded on a common understanding.

In AEC, the e-COGNOS project (COnsistent knowledGe management across prOjects and between enterpriSes in the construction domain - IST-2000-28,671) [76] implemented an early deployment of domain ontology for knowledge management, by incorporating the ontology in a comprehensive knowledge management system. The ontological model grounded on “a group of Actors uses a set of Resources to produce a set of Products following certain Processes within a work environment (Related Domains) and according to certain conditions (Technical Topics).” Accordingly, a construction Project is a collection of processes. Each Process had input requirements, that is the completion of all scheduled processes, the clearance of required approvals, the handling of required knowledge items (documents, software, etc.), the availability of required Resources (materials, equipment, subcontractors), and output requirements, that is update to a product time-line, update to the project schedule, update to the project budget, and update to the legal status of Actors. The knowledge management system implemented tools for the collaborative creation of document, search, sharing, dissemination, and documentation.

Further works had integrated Building Information Modelling (BIM) with ontology-based knowledge management. Ding et al. [77] modelled construction risk knowledge into an ontology-based semantic network for planning risk maps. The mapping of the risk-related knowledge supported the semantic inference between risks and risk paths. The knowledge is semantically linked to the relevant objects in BIM. Lee et al. [29] had semantically linked knowledge on unstructured construction defects with BIM objects to reduce the occurrence of defects by referring to the previous faulty cases.

In the field of renewable energies, Abanda et al. [78] developed a photovoltaic technology ontology system (PV-TONS) reusing and extending the ontology to manage knowledge about photovoltaic-systems, previously implemented by Tah and Abanda [79]. Saba et al. [80] implemented a tool to optimise hybrid energy systems (HES) based on a domain ontology.

2.4. *Logical inference and proofs*

The underlying logical foundations to ontologies rely on Web Ontology Language (OWL), a set of knowledge representation languages, based on Description Logic (DL). That is, OWL classes correspond to DL concepts, OWL properties to DL roles, individuals are named in the same manner in the OWL and the DL lexicon.

A coherent representation of the knowledge in OWL can use the initial knowledge to infer logical consequences and further instances. Besides, semantic reasoners can derive every consequence of the knowledge in an ontology, by providing a richer set of mechanisms to work with. Several reasoners use first-order predicate logic to perform reasoning, while probabilistic reasoners and probabilistic logic networks are emerging, using non-axiomatic reasoning systems [81]. “By introducing ontological reasoning, semantic techniques enable discovery of knowledge and information that was not part of the original use case or purpose of the ontology itself.” [76].

Kadolsky et al. [82], to simplify simulation in the energy-efficiency design of buildings, implemented the eeBIM ontology that provided the concepts for describing a building, the BIM objects, the external data (e.g. climate data), and the interrelations among them. From the eeBIM ontology, they inferred logical rules to pre-check the input data and to pre-analyse the energy performance, in advance of the simulation. The logical rules performed the consistency checking and the consequences assessment, for instance accomplishing the verification for compliant thermal insulation:

“the model checking each process is related to a set of logical rules specifying restrictions, cardinalities, etc. for the domain model and environment model schemas. These logical rules represent the requirements the given models and their instances have to fulfill for the related process. The environment and domain models with their certain instances represent the resources, which have to follow the given model schema and the related rules. Thereby, two processes can be related to the same model-schemas, but to different logical rules. This would mean that the processes are operating on the same domains and the same environment, but they need a different view for the process execution. So, the process model comprises both the ‘To-be’ description represented by the model schemas and logical rules and the ‘As-is’ description represented by the model instances.”

Kuster et al. [83], to support real time assessment of urban sustainability and to inform decision-making, developed the Urban District Sustainability Assessment (UDSA) ontology. At district level, the ontology links sensors, GIS and BIMs models, and regulations such as Leadership in Energy and Environmental Design for Neighbourhood Development, Building Research Establishment Environmental Assessment Method, and Comprehensive Assessment System for Built Environment Efficiency for Urban Development. The validation has been performed on the site of “The Works”, a newly refurbished neighbourhood in Ebbw Vale, Wales. The flow of data came from local district heating with heat provided by a combination of CHP units, biomass boilers and gas boilers, including the energy provision and the measures of heat and electricity production and of the demand from the specific buildings. The ontology performed the query of the data, where a time series is managed as a single observation. OWL 2 reasoning engine inferred both explicit and implicit relationships over the series. Because of the cumbersome number of observations, the OWL instances proliferated beyond computability. Thus, Kuster et al. moved to OWL 2 QL that allows reasoning over a large volume of instances, at the cost of some reduction in expressivity: “Therefore, some axioms remain, such as subclass axioms, equivalences, inverses, properties etc., whereas some others, such as transitivity, cardinality restrictions or universal and existential restrictions, are not supported.”

3. Layouts generation: separating knowledge from process

For the generation of layouts, we have separated the knowledge about the objects, the spatial relationships, and the constraints from the generative process.

The separation between the knowledge and its possible practical uses is important, because – as considered in 1. Introduction – a large body of knowledge, spanning various aspects across buildings and cities is being implemented into formal ontologies. Artificial Intelligence has developed ontologies as effective tools for separating the knowledge in a domain from its uses.

The present study has reused existing knowledge, used for layout generation, from two existing ontologies (cf. 4.).

The generation process has been addressed in the more general geometric constraint-satisfaction problem [84,85]), which can deal with the general problem of layout of objects in space matching constraints and relationships, in which the plans are not bound until the CSP is solved by the constraint satisfaction solver.

4. Knowledge for layouts generation

The research has used two existing ontologies. The next Sections describe the Urban Morphology Ontology (UMO) [71], and the Semantic Tools for Carbon Reduction in Urban Planning (SEMANCO) ontology [58,166].

4.1. *Urban morphology ontology: the basic units and their relationships*

For the formalisation of the UMO, Berta et al. [71] recognised four reference classes that map the hierarchical main morphological levels of objects:

"Those classes have been defined trying to catch the hierarchical main levels of urban elements that appear in an 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 open and non-covered space), volumes (i.e. every building over covered 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 elements, such as *building*, *green* etc.

Subclass 2: **Architectural typologies.** This class articulates the typological peculiarities of the entities, such as *semi-detached building* 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.

The definition of the Classes only does not provide enough information for the arrangement of objects into layouts. To extend the description with morphological knowledge, relationships between objects are defined.

UMO implements five different types of relationships between class individuals:

- hypernym-hyponym relationships (subclasses and superclasses);
- holonym-meronym relationships;
- pertinence relationships;
- spatial relationships;
- size relationships.

The relationships are further defined with data properties that include, for example, morphological descriptions, detailed at the level of the individual instances in the ontology."

UMO is accessible on the WebProtégé server [86] which supports collaborative editing, under CC BY Creative Commons license, and as Mendeley Data [87].

4.2. Semantic tools for carbon reduction in urban planning ontology: the basic units and their relations

The formalisation of the SEMANCO Ontology considered three reference forms of concept relationships: "the generic relation, the partitive relation and the associative relation. In the generic relation, the subordinate concepts within the hierarchy inherit all the characteristics of the superordinate concept, and contain descriptions of these characteristics which distinguish them from the superordinate (parent) and coordinate (sibling) concepts." [58].

The relationships had been used to structure the energy and environmental data, into categories and fields. The leading categories referred to: energy quantities, energy costs, climatic conditions, air pollutants, legislative constraints, geographical position, land parcels and use, land tenure and value. The data fields are either common, applicable to all the data, or specific, for instance peculiar to a context, project or application.

The ontology enabled semantic tools to access the data stemming from different domains and applications:

> "to 18 technical standards, covering 25 different domains. Each standard provides from 1 to 52 terms to the vocabulary (…) In relation to the total number of terms defined in the Energy Standard Tables and included in the ontology, each standard provides from 1% to 5.3% of all terms. However, one term can refer to multiple standards. The standards which have been most applied in the Energy Standard Tables are ANSI/ASHRAE/IESNA Standard 90.1, SAP, LBCS Standards, ISO/TR 16344, FprEN 15603, EN 15316, DATA-MINE and TABULA (determining more than 30 terms each)." [58].

The SEMANCO ontology in accessible as Mendeley Data [88].

5. Process for layouts generation

5.1. Background to layout generation

A large body of studies has considered the generation of layouts. This plurality is motivated partly by the several different aims of simulation and design, and partly by the multiplicity of the methodologies experimented with. A possible broad differentiation can distinguish between methodologies aimed at generation for planning and construction purposes and those aimed at generation for visual realism, e.g. in motion pictures and video games. The first have the pragmatic intention of giving the designers the ability to control the options with the aim of generating the best layout. This is a reduction process from the huge number of options open to designer's choice towards a circumscribed set of parameters that are able to control the process. It is often grounded on the analysis of existing processes and layouts and the effort to describe them possibly with a reduced set of features. Generation for visual realism aims to deliver an experience with such a level of detail and textured appearance of materiality that "audiences could surrender completely to it" [89].

Without the ambition of considering such a huge domain exhaustively, in the next Sections we consider production rule systems, fractals, cellular automata and declarative.

5.1.1. Production rule systems

A shape grammar is understood as a form of production system [90] that defines how an initial shape is transformed by successive (recursive) application of transformation rules.

> "In order to construct feasible solutions, developers need to extract the characteristics of desired designs and allocate them to the rules in a certain logic. Obviously, most expert grammars belong to this kind. There are mainly three requirements for object representation: feasibility, diversity and efficiency. Generally, feasibility is achieved by semantic information and constraints. For example, in his design grammars for urban planning, Beirão et al. [91] built ontologies to organise the semantics of design objects and combined constraint descriptions with shape rules to guarantee that designs comply with specifications" [92].

Duarte et al. [93], for the generation of the historical urban tissue in Marrakech Medina, advance a detailed shape grammar, consisting of more than sixty transformation rules with their respective control parameters. In the Medina case, the generation of the road network mainly defines the layout of the blocks and plots. The generative role of streets and squares in the shaping of the urban tissue is further extended and generalised in Duarte's later works, for instance with the definition of an ontology "generated by urban induction patterns (UIPs), which are grammar-based algorithms replicating typical urban design moves that urban designers apply recurrently" [91]. The root classes in the ontology are four generative patterns, respectively of axes, networks, squares, and urban units.

Beirão [94] advances a generalisation of the method of urban design with a four-stage approach:

> "(1) identification of territorial features that could establish the plan guidelines and the rules for producing them, (2) the rules for designing the urban grid or grids, (3) the rules for designing urban

> units, considering these to be identifiable units of urban elements from the neighbourhood to the urban block and (4) the definition of rules for designing the plan details. Shape grammars were presented as a possible formalism for expressing the design rules at any moment in the design process".

Al-Sayed et al. [95] defines four basic transformation rules – addition, pruning, mergence, and subdivision – that are applied in "a positive feedback loop that results from the addition of new elements and a reinforcing feedback loop that results from pruning certain elements". Their configuration parameters are controlled by topological, geometric and metric relationships, whose definition is supported by the analysis of urban fabrics.

Parish and Muller [96] in CityEngine implement and develop a production rule system, initially introduced by Wonka et al. [97], which extends the grammar and the general rules of L-systems. The extension aims to reduce the growth of the number of rules and conditions, by means of the "ideal successor".

> "When writing a complex rule system to create a street map, there are a large number of parameters and conditions that have to be implemented to the L-system. The number of productions and their complexity grows very quickly. Every time a new constraint is implemented, many rules have to be rewritten. This makes extensibility a very difficult task. Thus, instead of trying to set the parameters of the modules inside the productions, the L-system creates only a generic template at each step. We call this generic template the ideal successor".

The grammar uses general rules, such as add, rotate, scale, and translate, common to L-systems, implemented with a sequential processing, to model the description of structures, peculiar to road networks and buildings [98].

CityEngine gives the user the control of the global patterns of the roads using 2D tensor fields, to generate ideal-typical tissues, e.g. grid, radial, along a boundary, and their mixes [99]. The tissues can be modelled indirectly by inserting local vectors, which are a generalisation of the tensors, or directly by reshaping specific roads.

Several shape grammars have been developed for the generation of floor plans. Hou and Stouffs [92] recognise shape grammars for:

- analytical aims, to generatively reproduce a specific architectural style, Palladian houses [100], Frank Lloyd houses [101], and Alvaro Siza's houses [102];
- synthesis aims, to generate new designs, for instance play wooden building blocks as generative elements of design [103], rectangular floor plans [104], floor plans matching constraints defined with a Bayesian network [105] or placing requirements for objects [106,107].

5.1.2. Fractals

Several research studies, just a few of which are mentioned below, have analysed the fractal dimensions of road and transportation networks [108–111].

For a generative approach, Chen and Liu [112] have implemented a fractal generative system based on two processes: iterating and fractal. The iterating process starts with settling buildings, streets, and squares, through dividing an area into an "area-list". The fractal process "starts at on each element […] in above area-list, and goes on the same process until terminated condition is satisfied. The terminated condition can be threshold size of area when it can be used for constructing building, road, lawn etc.". The road network and, more generally the public space, emerge by subtraction of the built. Meanwhile Thomas and Frankhauser [113] in their research focus "on the relationship between the spatial distribution of built-up elements and the spatial organization of the street network at the scale of city districts".

The fractal dynamics of transportation networks and, more generally, of urban morphologies have been associated with diffusion limited aggregation (DLA) [110,114]. Batty et al. [115] has advanced a DLA model to generate the growth in the form of dendritic structures by several sub-clusters of roads, without links between them.

Erickson and Lloyd Jones [116] have introduced a conditional clause in the generative process: after the addition of a new street trunk, the surrounding area is checked for existing streets, which are then linked to the new one.

5.1.3. Cellular automata

The DLA process has been transferred to the description of the evolution of a road network over time. Toffoli and Margolus [117] start with an empty space, a two-dimensional regular lattice of squares. The network grows step by step according to a Cellular Automaton (CA), whose nodes are the crossings, connected by edges, the paths, within a given distance r, which is the radius of the neighbourhood area under consideration. A new step is created according to connecting rules that determine that two nodes are connected by an edge depending on the number of nodes in their area, and on their respective distance, greater than r [118,119].

5.1.4. Declarative

The declarative approach to road modelling aims to shape networks consistent with their description in terms of properties and constraints. The descriptions can be composed out of geometric, topological, and semantic knowledge [120].

Liège and Hegron [121] define a declarative model of roads described according to their properties, within one street, between two streets, and among several streets. The network is being described "in a hierarchical and incremental way" [122]. The user begins with an approximate sketch, formalised by means of a description language, giving only the main features such as the main roads and crossings. "This description is used to propose one or several solutions that the designer can refine." The scene description is translated in a constraint graph which is instantiated to produce a solution using constraint propagation with backtracking and a scene generation model. Finally, a geometric model (2D map) is extracted from the scene generation model. This process is repeated in a hierarchical and incremental way, starting from a crude description of the scene up to more refined layout descriptions.

5.2. Implemented layout generation

Our implemented layout generation process derives from work on the Constraint Satisfaction Problem specifically the Geometric Constraint Satisfaction Problem (GCSP) [84,85].

In a GCSP the constraints refer to object, to place and to size [123]. In our current implementation, a set of constraints are context- and/or user-defined, and concern:

- Geometric constraints refer to layout shape, dimensions and area constraints, and to objects, morphology and relationships that derive from classes and their relationships in the ontologies (cf. 4.);
- Adjacency constraints derive from relationships between objects, e.g. accessibility, distance, connection and nearness that express the spatial relations between entities in the ontologies;
- Network constraints relate to movements of people, objects, or energy that are defined by transportation-means and -networks [124–126].

5.2.1. Geometric constraint satisfaction algorithm

"Layout generation problem (LGP) is a typical design problem which can rely on recurrent operations to yield diverse solutions that can be quantitatively evaluated." [1].

A Constraint Satisfaction Problem (CSP) [84] is defined by a triple (X, D, C), where:

1. *X* is a finite set of variables.
2. *D* is a function that maps each variable *x* in *X* to a finite set of values *D (x)*, which it is allowed to take. The set *D(x)* is called the *domain* of *x*.
3. C is a finite set of constraints, i.e. relations, that are assumed to hold between the values of the variables. These relations can be given intentionally, i.e. in a symbolic form such as predicate logic, or extensionally, i.e. as an explicit enumeration of the tuples that are allowed by the constraint, or procedurally, i.e. with an appropriate generating or recognising function.

Since in GCSP, all the constraints are instances belonging to objects, places or their relationships, a CS problem is usually represented as an undirected graph, called *Constraint Graph* in which each node represents a variable in X and there is an arc between any two variables that are related by a constraint. Unary constraints can be disposed of by just redefining the domains to contain only the values that satisfy all the unary constraints. The constraint graph is also called a primal constraint graph [127]. For CSP with only binary constraints there is a direct association between arcs and constraints. To maintain this association for general constraint networks, we need a *Constraint Hypergraph* representation, in which for each constraint there is a hyperedge S that represents the constraint.

The constraint satisfaction problem is to find an instantiation of all variables in X so that all constraints are satisfied.

5.2.2. Tessellation algorithm

Convex Optimization [128] has been implemented in order to generate a tessellation representing the layout of the objects. The tessellation step defines the value of a subset of our GCSP variables, i.e. the variables representing the position and the size of each object inside a layout.

Our implementation generalises the methodology adopted for fixed outline floorplanning in nanometer integrated circuit technology [129], defined by Lin and Hung [128]: they optimise the total wirelength, a sort of global adjacency condition is applied to all the modules through the minimisation of the cost function Our algorithm also takes into account geometric and adjacency constraints between objects and network distance constraints, as well as for the layout area:

- the shape (if given),
- the dimensions, and
- the constraints.

The electronic modules of the floorplanning are replaced by the objects in the present implementation of the algorithm.

Furthermore, we have generalised Lin's method, taking into account non-rectangular layouts too. In Lin's algorithm, to optimise the total wire length, a sort of global adjacency condition is applied to all the modules through the minimisation of the cost function. In other words, this ensures that the circles that represent modules have been uniformly distributed over a specified region. Our algorithm can also arrange clusters of objects into superstructures, e.g. into on-site tasks, rooms, buildings or plots. The users can direct the aggregation process by defining which objects or activities must be adjacent to each other to cluster them.

The problem of a superstructure with a rectangular contour has been broken down into two phases: a stage for uniform distribution and adjacency-network constraints, followed by a placement and shaping phase, in which objects are aggregated into clusters in an interactive way. The first phase consists of two steps:

- In the first step M area clusters are identified, based on the adjacency-network constraints. A circle C_i is assigned to each cluster with radius r_i proportional to the square root of the total cluster area A_j. We have set the value of the radius equal to the radius of the circle inscribed in the square of area A_j. The PP model proposed by Lin has been generalised to uniformly spread the clusters on the superstructure surface, also dealing with the constraints on the positions of the clusters inside the superstructure (Fig. 1a). These conditions can be directly inferred from the constraints on the placement, defined by the user, e.g. if an object must be on the Northern side of a layout, this is also true for the cluster which contains the objects.
- In the second step each cluster is exploded in N sub-circles with radius r_i proportional to the square root of the corresponding area a_i (in this case also we have set this value equal to the value of the radius of the circle inscribed in the square of area a_i). Lin's PP model has been generalised to spread the circles on the superstructure surface managing their correspondent position and adjacency-network constraints defined by the user (Fig. 1b). Adjacency and network constraints inside each cluster are satisfied using a deterministic dynamic approach.

Both in the first and in the second step the designer can interact with the diagram to reallocate the circles. After the second step, the user can also interactively define the main accessibility paths or axes and their topological relationships with the objects. After the first stage, the circles that represent objects have been uniformly distributed over the superblock area and the constraints are satisfied. In the second phase we have to determine the exact locations and shapes of objects so that no two objects overlap and all the plots are placed inside the superstructure. This phase has been subdivided into three steps:

- In the first step we extract geometric relations of objects from the circles' distribution and record them by constraint graphs, as in the DT method [130]. We have generalised the DT graph in order to deal with the topological relationships between axes and objects defined by the user in the previous stage.
- In the second step, according to the constraints defined in the constructed constraint graphs, we use a constrained nonlinear optimisation algorithm to reshape the clusters so that objects can be placed inside the superstructure and no two objects overlap (Fig. 1c). The sum of the squares of the differences between the areas and their nominal values defined by the user has been chosen as objective function. Furthermore, the constraints on the maximum and minimum values of each area and on the ratio between the dimensions of each object are taken into account.
- In the third and last step, the designer can interact again with the diagram to define the minor paths. We use a constrained nonlinear optimisation algorithm to reshape the layout again in order to generate minor paths, when interactively defined by the user, and to eliminate (optionally) room between objects (zero dead space), by smoothly relaxing the constraints used in the previous step and by respecting the constraint on the minimum distance between accessibility axes (Fig. 1d).

The algorithm can deal with pre-placed objects easily due to its mathematical formulation, better than in Lin's algorithm. Since the coordinates of pre-placed objects are known, we only need to assign the values to the centres of the corresponding circles in the global distribution stage, as in Lin's algorithm. All circles can be moved arbitrarily except these circles which are placed on the fixed locations by means of two linear constraints on their centre coordinates. Since we give aspect ratio constraints for areas during the placement and shaping phase, we can also give them for pre-placed modules. Therefore, they cannot overlap with other modules at the end of the legalisation phase and we don't need to adjust the shapes of modules overlapped by them as in the Lin algorithm.

Finally, we have used an approach based on the Szegö projection [131] in order to obtain a solution for non-rectangular layouts too. The solution for the first stage of the problem is first calculated in a rectangular area, based on the algorithm for the first stage discussed above. The rectangular area is that one that best approximates to the original

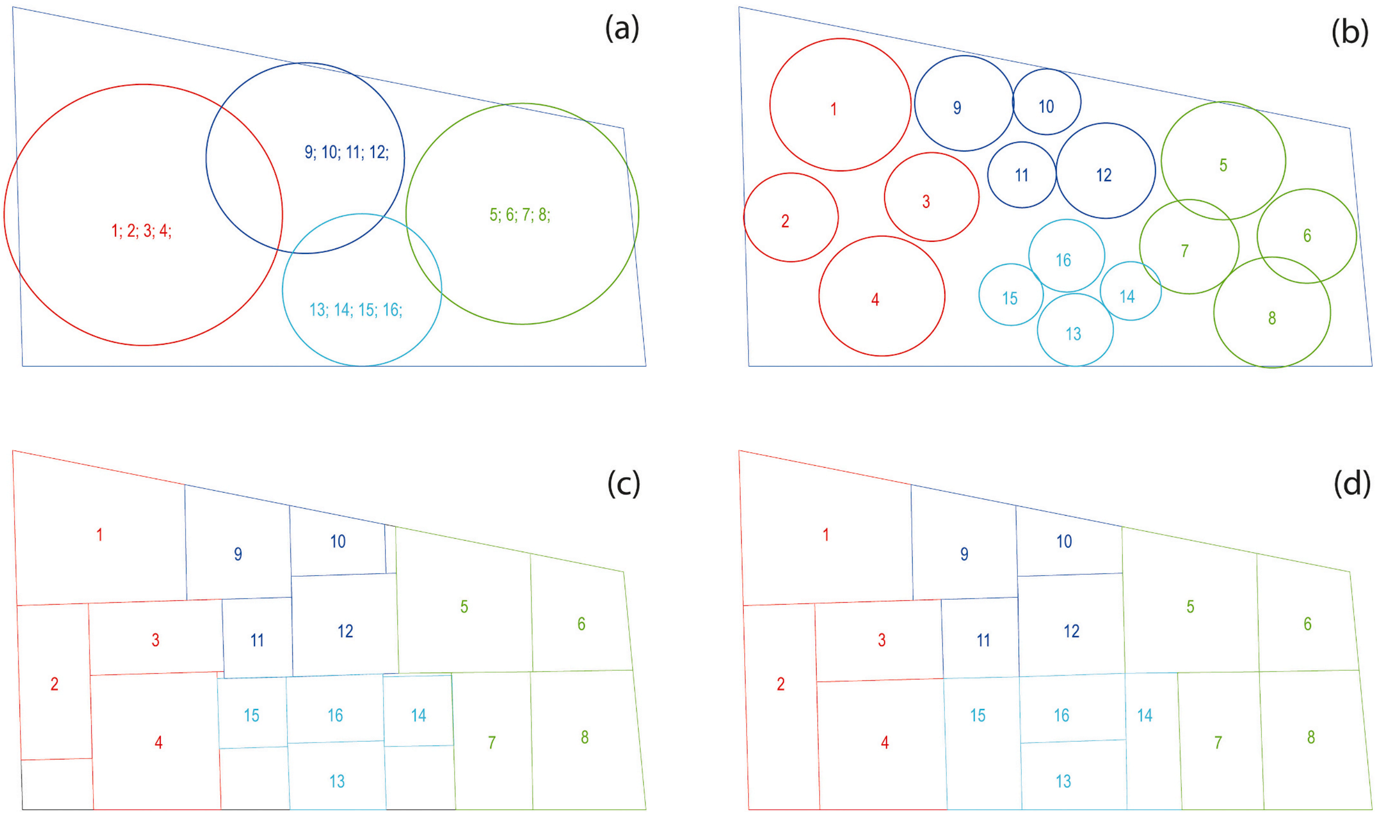

Fig. 1. Four steps of the implemented tessellation algorithm.

layout. Dummy pre-placed objects are used when the original area has a shape very different from a rectangular area. Then, the solution is transformed by means of the Discrete Cauchy-Green transform [131] to obtain the (approximate) solution in the original layout.

In the second stage, the problem is solved by using as the rectangular area the bounding box of the original layout.

6. Linking knowledge to process

The knowledge about the constraints on the layout and objects is imported from the ontologies. In the ontologies they are represented as classes and their relationships. Specifically, the ones in the two existing ontologies are considered (cf. Section 4.).

The constraints are formally defined with Semantic Web Rule Language (SWRL). SWRL combines sublanguages of the OWL Web Ontology Language (OWL DL and Lite) with those of the Rule Markup Language (Unary/Binary Datalog). The formal foundation to OWL DL is provided by Description Logic. The reference classes in the ontologies correspond to concepts in Description Logic, where the properties match the DL rules.

Rules are of the form of an implication between an antecedent (body) and consequent (head). The intended meaning can be read as: whenever the conditions specified in the antecedent hold, then the conditions specified in the consequent must also hold. At present, reasoners do not support the full SWRL specification, because the reasoning quickly becomes undecidable. We used Pellet, an open-source Java OWL DL reasoner, which has SWRL-support, to check the consistency of the ontologies. In particular we checked the consistency of the constraint definitions with the restrictions of the ontology concepts used to define them.

For the purposes of layout generation for an eco-industrial park (EIP, cf. 8.1), UMO provides four reference types of constraints:

- Topological constraints,
- Dimensional constraints,
- Directional constraints,
- Distance constraints.

The classes, imported from UMO, are highlighted in red in Fig. 2.

SEMANCO Ontology provides constraints, categories and fields for the layout matching waste heat reuse in an EIP, according to industrial symbiosis. To reuse heat at different levels through networks –intra-company, inter-company, and with neighbouring communities– SEMANCO instantiates the fields for the categories (cf. 4.2). The leading types of constraints imported from the ontology are about:

- energy systems, energy quantities and boundary condition data, namely energy, climatic, and building technical classes and data;
- energy-related or contextual data, i.e. energy cost, environmental, legislative constraints, and geographical data.

The classes, imported from SEMANCO, are highlighted in red in **Fig. 3**.

For the sake of generality in industrial symbiosis of energy, SEMANCO delivers to the layout generation process broad definitions of classes and datatypes. Meanwhile, the Open Energy Ontology has been put forward [133]: it provides a common description of knowledge and vocabulary across domains and different modelling approaches.

OntoEIP [134] implements different classes of power generator and energy market aspects, besides OntoPowSys [135] extends the classes and properties hierarchy to electrical power systems.

At the level of the individual instances, the constraints are defined by means of both qualitative and quantitative properties. Qualitative constraints are expressed by directional, nearness and RCC (Region Connection Calculus) topological relationships. Quantitative constraints are expressed through equations or inequations in Cartesian, longitudinal and polar coordinates.

For each layout-project, a set of variables (numerical properties) was

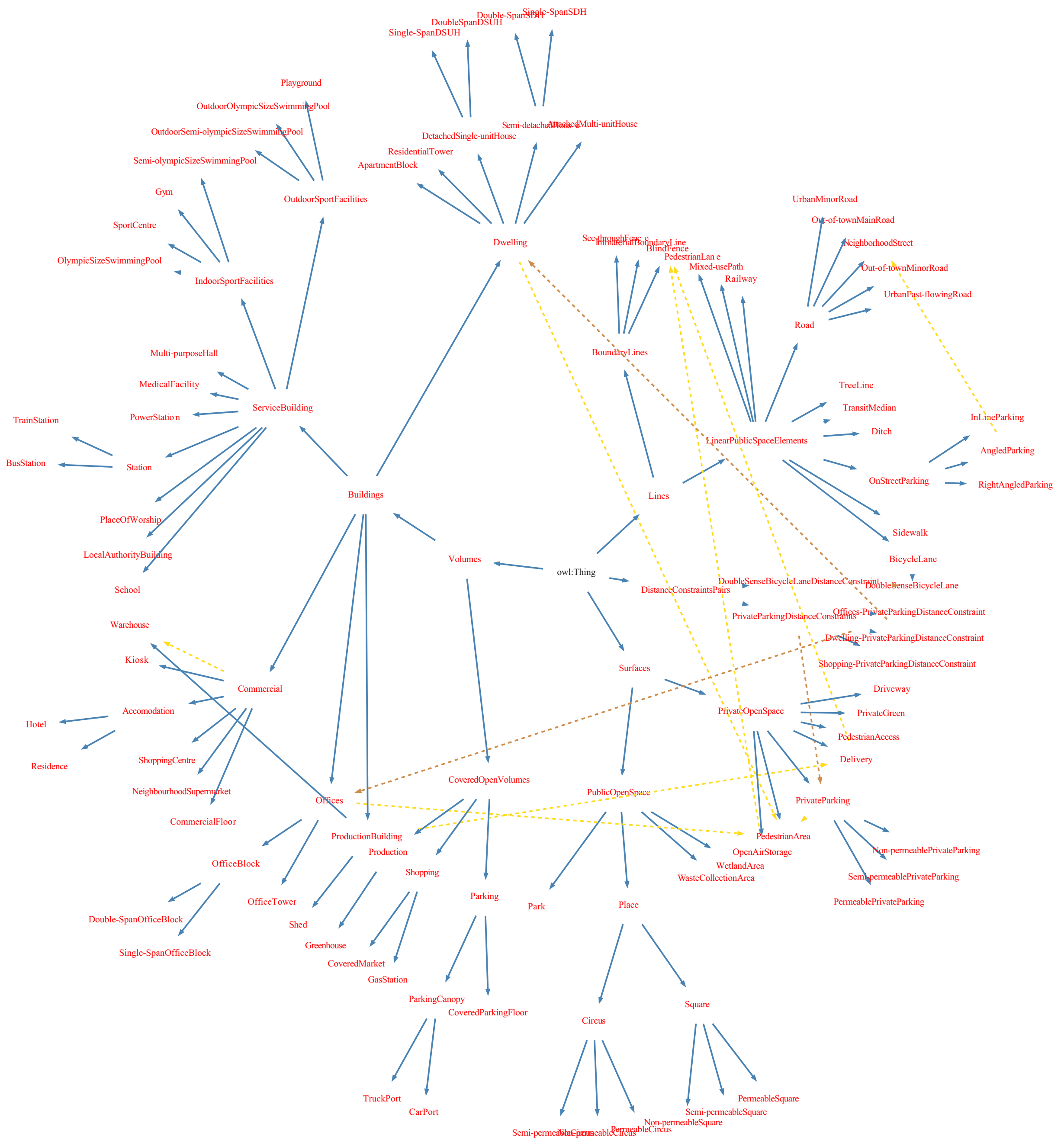

Fig. 2. The structure of Root Classes and Subclasses in the Urban Morphology Ontology. The relationship between a Class and a Subclass is represented with a blue solid line, between a Class and an external Class with a dashed brown line, between a Class and an external Subclass with a dashed yellow line.
The Classes used in the generation of the layouts are highlighted in red.
Readers are invited to explore object properties, data properties, and datatypes in UMO [87] with Protégé [86], OntoGraf [132] or other OWL visualisation tools. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

defined for the GCSP problem. For instance, they could be plot shape, buildings footprints, front size, gross floor surface, number of floors, energy costs, climatic conditions, normative, and so on.

The variables were grouped into dependent variables and independent variables, and related to each other by means of the quantitative constraints. For the system users, independent variables assume the meaning of “layout parameters”, whose values they can play with, to generate different arrangements of layouts.

7. Generative process

To integrate the generative process into the earliest phases of the design, we implemented the system on top of SketchUp, because it offers an established GUI that is widely appreciated for its intuitiveness and ease for manipulating and editing designs in 3D.

For the sake of integration, the object definitions were created with a declarative programming approach. Declarative programming style is, in fact, more appropriate than imperative style to represent the background declarative knowledge in the ontologies. The elements of each object in the layout define a meronymic taxonomy of geometrical forms, placed on the layout according to the ontology constraints. This characteristic allowed us to create the objects in SketchUp as Dynamic Components. SketchUp Dynamic Components are parametric definitions of specialised and structured set of components to which attributes have

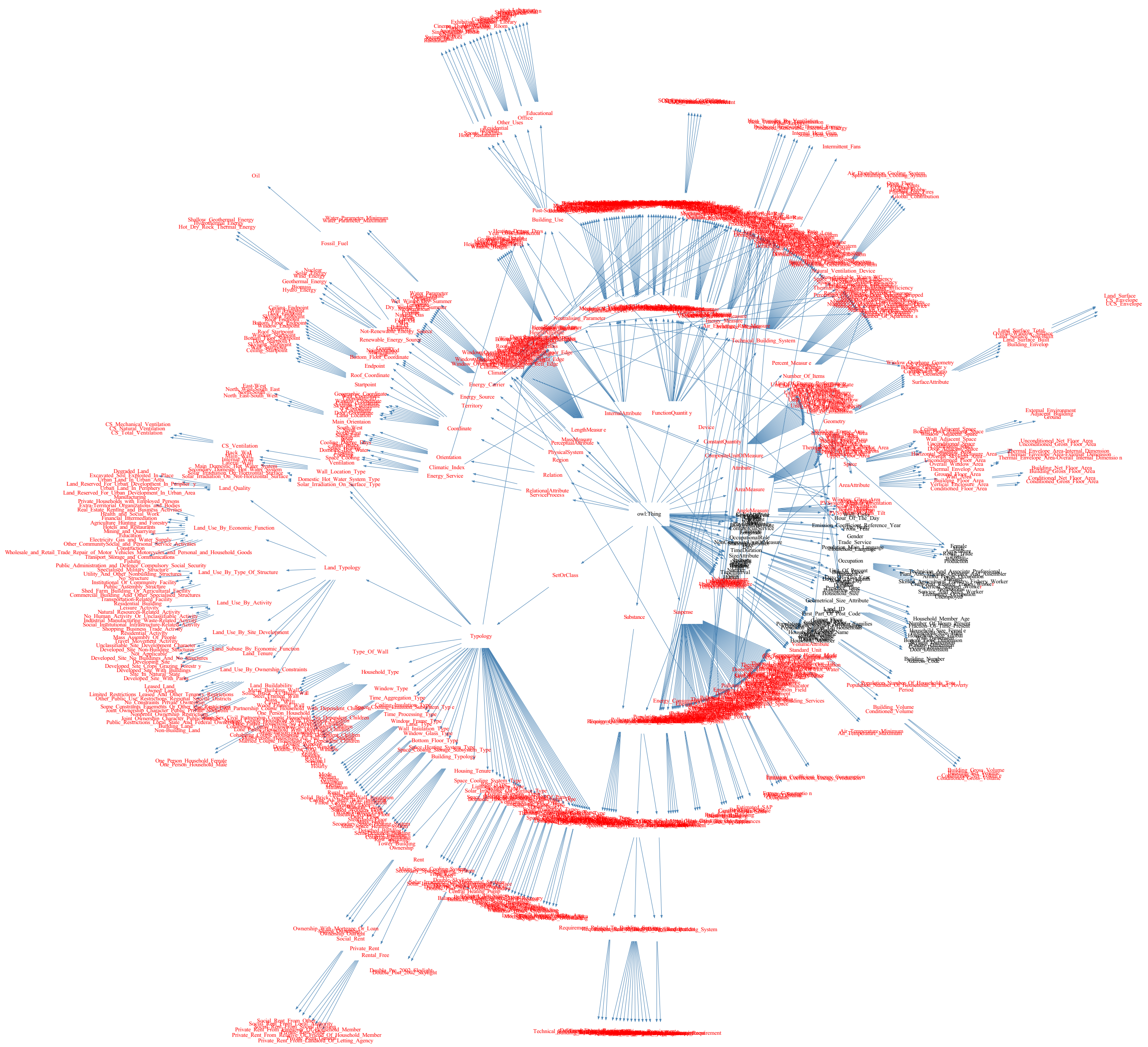

Fig. 3. The structure of Root Classes and Subclasses in the SEMANCO Ontology. The relationship between a Class and a Subclass is represented with a blue solid line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
The Classes used in the generation of the layouts are highlighted in red.
Readers are invited to explore the ontology personally [88].

been assigned by means of a Ruby based geometric description language. Attributes can also contain spatial relationships between components (quantitative relationships such as Cartesian, longitudinal and polar relationships), and behaviours (like smart scaling). Object instances are set up to be fully reconfigurable by the user after their generation via a dialog interface box. The CSP solver of the SketchUp Dynamic Components was used to generate the layout instances satisfying the GCSP problem constraints.

7.1. Semantic generation

The system is able to generate all the layout instances fitting the GCSP problem constraints. The constraints on and the relationships among the layout and objects are set in the ontologies (cf. 6. Linking knowledge to process).

The set of knowledge about objects and the set of knowledge about spatial relations in a domain give rise to the process of generating layouts. Layouts plural, because the methodology is not designed to generate a single arrangement, rather it produces a plurality of solutions, all compliant with the knowledge within the ontological formalisation.

In Gero and Sosa [136] the set of all the compliant layouts has been termed a design space:

> “Modern design theory views the design process as a search in a predefined space of possible designs [137]. This design space is implicitly fixed by defining its generator (a process that can generate any design in this space). This notion of design space has played an important role in formalising designing and the processes that can be computationally implemented ([138; 139])”.

Very often within a design space, more than one layout can fit the designers' and stakeholders' requirements. For instance, layouts can differ in the detachment distance from the border of the plot, the dimensions of the objects, the gross floor area, the coverage ratio, and so on. Moreover, small changes in a single variable or in the combinations among variables can produce dramatic differences in the layout.

Our working thesis is that the plurality of generated layouts gives greater flexibility to stakeholders in defining and matching their requirements, and to designers to explore a wider range of hypotheses in the view of a greater control over variety and choice. Often AEC and Smart City projects involve a large number of different actors, pursuing competing, diverging or conflicting objectives. Multicriteria decision analysis (MCDA) has been used to formalise the design space, to improve the decision-making process, and to make it clearer. MCDA focus is on the process and on the decision-makers (DMs). If the process aims to match the best layout, possibly within predefined subsets, then multi-attribute decision analysis is applied [140]. Conversely, when the aim is the systematic exploration of alternatives fitting designers' or DMs' objectives, Multiobjective decision analysis (MODA) methods are used [2–4].

Generating layouts fitting multiobjective criteria implies that a finite set of equally interesting Pareto optimal solutions can be found, instead of a single optimal solution. Within a design space a Pareto set, also known as a Pareto front, defines all the layouts that cannot be improved in one criterion except at the cost of depreciating the value for another criterion.

Semantic generation is able to generate all the layout instances, and within them an algorithm can identify all the Pareto optimal ones. Miettinen, [2], Hwang and Masud [3], and Branke et al. [4] have used the description "a posteriori" for methods which identify all the Pareto optimal solutions, and generate their representations. For stakeholders and designers, the advantage is a whole picture of all the available alternatives for the layout.

Since the semantic generation runs in SWRL, on top of OWL DL, and the OWL DL reasoner is able to efficiently check consistency and to generate all the compliant instances (cf. 6. Linking knowledge to process), the computation effort is reasonable and time effective for a real decision making-process.

Many real-world projects are affected by a plethora of external factors, e.g. market fluctuations, economic externalities, environmental-weather conditions, human mistakes of omission (errors made by not taking the right evaluations) and mistakes of commission (errors made by taking the right evaluations in a wrong way). Appropriate management of the uncertainties is critical to the successful completion of projects.

The main sources of uncertainty relate to:

- Parameters, "the values of parameters are not known at the time a problem is solved" [141] or can change over time. Eichfelder et al. [141] and Zhou-Kangas et al. [142] address parameter uncertainty with "ranges characterized by best and worst objective function values describe the variations due to the possible perturbations in the decision variables."
- Decisions, "Decision makers often describe their preferences rather ambiguously. Further, experts who formulate decision problems as multiobjective programming problems often express parameters of the objective functions and constraints imprecisely." [143]. Decision makers can change their minds or objectives, due to a better understanding of the design space and the Pareto front. That is to enable conscious decision, which is one of the long-term aims of MODA. The uncertainties can possibly be even greater in early stages of design process.

Uncertainty affects the stability of the Pareto set, and can undermine the decision-making process. To address the decision uncertainty, we generate the representation of the Pareto front, and present it to the DMs who can interact with it. The DMs interact with the criteria, to visualise how the layouts change accordingly.

The literature on visualisation for MODA has addressed the means to represent the Pareto optimal solutions to the DMs, particularly when more than three objective functions are considered [144–146]. Among the visualisation techniques to enable designers and DMs to explore the multidimensional design space generated by the system, we have custom-developed parallel coordinates plot [147]: each variable is represented as a vertical axis with the ranges of values increasing from the bottom of the axis to the top.

In the Euclidean plane R2 with xy Cartesian coordinates, N copies of the real line R labeled $\bar{X}\,1, \bar{X}\,2, \ldots, \bar{X}\,N$ are placed equidistant and perpendicular to the x-axis. They are the axes of the *parallel coordinates* system for the Euclidean N-dimensional space RN, all having the same positive orientation as the y-axis.

A point $C \in$ RN with coordinates $(c1, c2, \ldots, cN)$ is represented by the *complete* polygonal line $\bar{C}$ (i.e., the complete lines containing the segments between the axes) whose N vertices are at $(i-1, ci)$ on the $\bar{X}\,i$ -axis for $i = 1, \ldots, N$ [148].

Several axes can be accommodated in parallel, and the data are plotted on these axes; this is the origin of the term "parallel coordinates". The corresponding points are connected with polylines. Each polyline represents a single data dimension, and lines crossings 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 specific layout is represented as one polyline whose vertices intersect the parallel axes: each intersection point identifies the value of the corresponding criterion.

To analyse several criteria simultaneously, many axes can be placed side by side. On the other hand, plots with large Pareto sets can turn chaotic: the familiar "spaghetti" graph of polyline congestion. To facilitate the simultaneous analysis of large Pareto fronts, in the online version we have implemented interaction techniques (**Fig.** 4). These techniques aim to enable users to directly manipulate and interpret visual representations of the relationships among criteria and the generated layouts. Among the interaction techniques, the system implements visualisation of a design solution, multiple selection, and animation.

Visualisation of a design solution, the user can move the mouse over a polyline to highlight it and to visualise the corresponding layout that is represented in plan and isometric views in two windows at the bottom-left corner of **Fig.** 4.

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 the two bottom-left windows. The user can control the speed of the animation with the movement of the cursor.

For example, let suppose that a designer/planner is considering the layout for an EIP. The user knows the dimensions of the area, the gross floor area, and possibly has in mind an approximate width of the front of the building. In the parallel coordinates plot, each objective turns into a multiple selection action over the corresponding criteria. The selection process highlights a subset of design solutions, that the system represents assigning a specific colour to the selected polylines (**Fig.** 4). Moving the cursor over this subset, the user can analyse the single layout and the values of the criteria over the axes. Alternatively, the user can interactively animate the selected subset, moving the cursor vertically over an axis. For instance, as the mouse slides over the axis representing the dimension of the frontage, the plan and the isometric views rapidly represent the different solutions that turn into an animation of the layouts, similar to a flip book, with the frontage extension of the building changing.

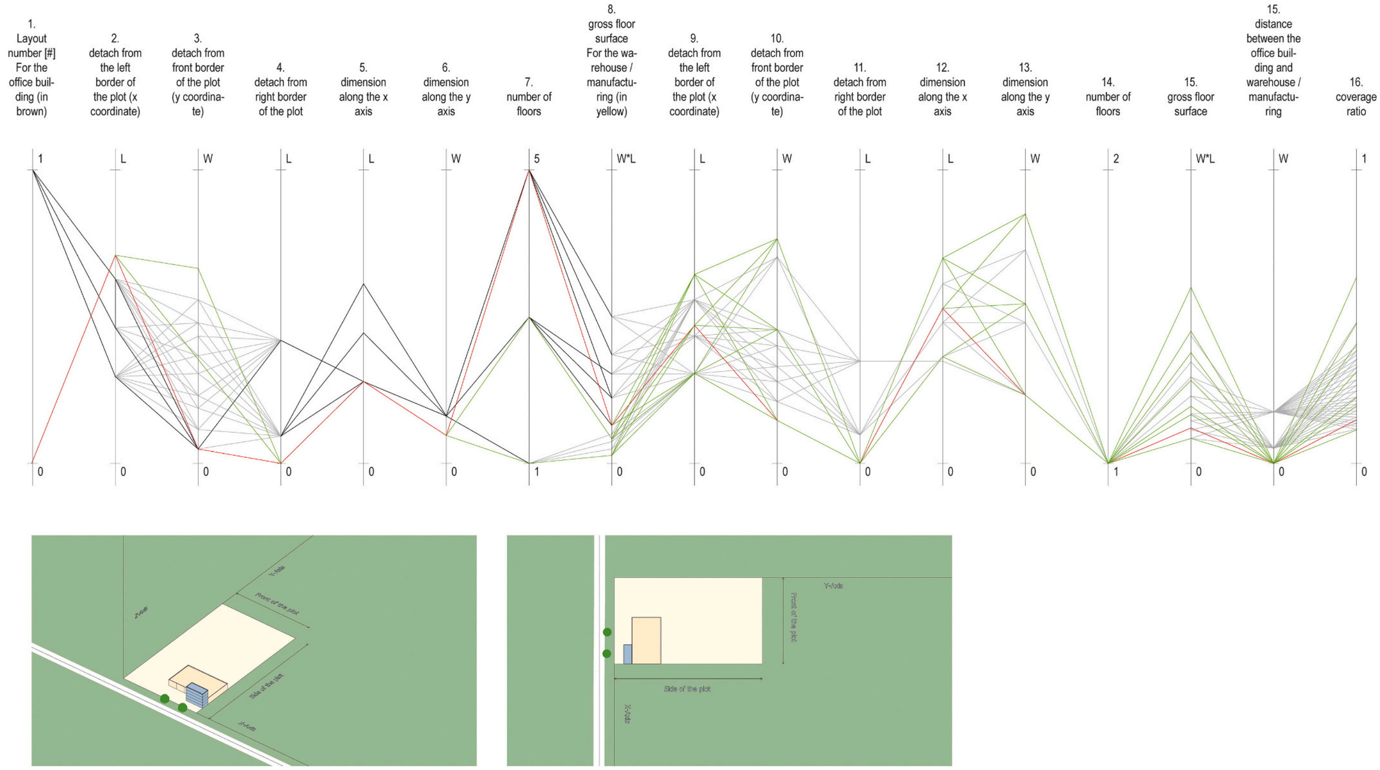

Fig. 4. Layouts for an industrial parcel in the EIP. Parallel coordinates plot with plan and isometric views in the bottom-left windows: selecting a polyline in the parallel coordinates plot displays the corresponding views of the layout in the windows. The variables on the vertical axes, from left to right, are (1) layout number, (2–15) for respectively the office building (in blue) and the warehouse/manufacturing (in yellow): detach from the left side of the plot (x coordinate), detach from front of the plot (y coordinate), detach from right side of the plot, dimension along the front of the plot, dimension along the side of the plot, number of floors, and gross floor surface, (16) distance between the office building and warehouse/manufacturing, and (17) coverage ratio. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

8. A case-study application

8.1. Case-study eco-industrial park

An early opportunity for testing the method and the system has been made possible thanks to an agreement between our Laboratory at Politecnico di Torino and the Municipality of Collegno, a town near Turin: the research team has been commissioned to study urban design alternatives for an eco-industrial park (EIP) on the northern border of the city.

EIPs are industrial-parks or -clusters where businesses cooperate inside the area and outside with the neighbouring communities. Applying the principles of industrial ecology and industrial symbiosis [149], EIPs set exchanges, reuse and valorisation of energy by means of exchanges between the companies in the EIP and with the neighbouring communities, to reduce waste and pollution, and seek for economic growth and economic benefits, with the aim of sustainability and environmental quality.

The new EIP covers an area of about 500,000 square meters, and is intended as a “buffer zone” between the existing industries and the nearby river park. In the intentions of the Municipality, the site should provide a close integration between industry, private/public services, and nearby neighbourhoods. The opportunities for and the characteristics of the new EIP are currently the subject of discussion between municipal and regional levels of public decision-making.

8.2. Methods and scope

For economic viability, EIP operation seeks optimality or quasi-optimality in functioning under a range of different industrial symbiosis processes. In the literature [150], the main types of symbiotic exchanges are: water, energy, and materials. In the case-project, energy exchanges have been mathematically modelled as reuse of heat at different levels through networks.

The modelling of the constraints has often proved sensitive to the parameter values [151]. As considered in 7.1 Semantic Generation, in the planning and managing of EIP, DMs pursue multiple objectives that can be competing, diverging or conflicting. In this context, the system has been used for generating different design layouts for the EIP, as DMs’ assessments of the objectives change (**Fig. 5**). The exploration of different Pareto fronts can be helpful in decision-making processes, to provide outlooks on layouts at the changing of several stakeholders’ requirements.

About one hundred businesses, interested in settling in the new EIP, have participated and contributed to the planning process. Their data and requirements were collected by the Municipality through questionnaires and interviews.

The system has managed the large number of stakeholders, objectives and criteria, generating all the compliant layouts. The challenges to the process came from:

- the plurality of DMs, arising from both the extent and number of activities in the EIP;
- the multi-scalarity of the public decision-making process, from local and municipal, to regional;
- the early stage of the process in the planning track, when most of the actors don’t have a stable understanding of objectives and of the tradeoffs and synergies among the criteria;
- objectives and criteria changed at a faster pace than the Public Administrations’ agendas and policies.

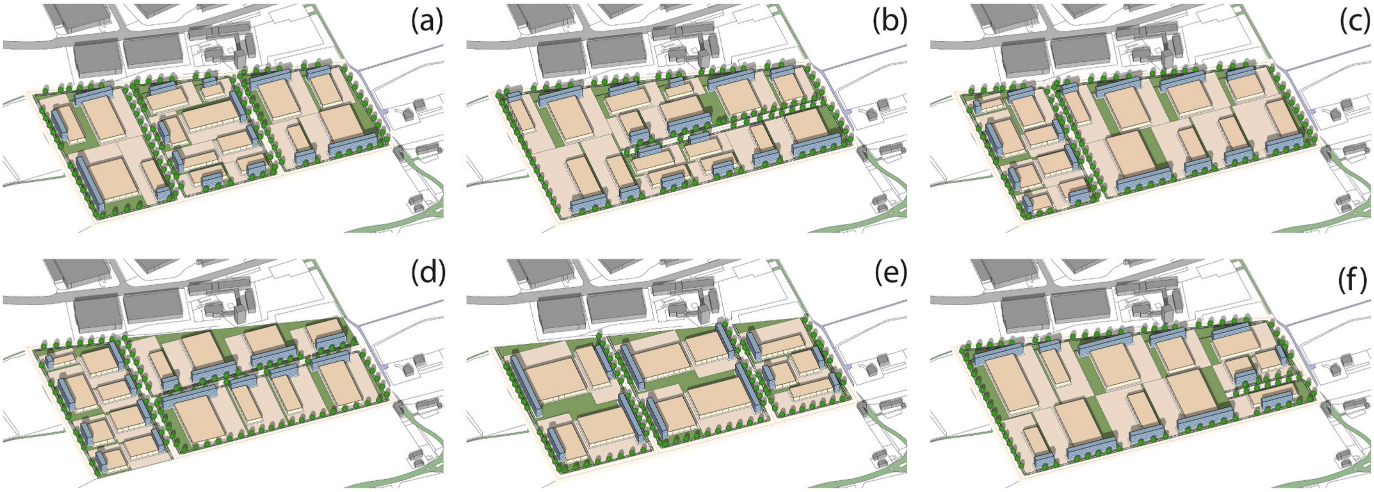

Fig. 5. The system rapidly generates and visualises the compliant layouts. Six Pareto-optimal choices of production out of the Pareto front, providing an outlook on DMs' set of criteria. In (a) and (b) every single land plot retains the same surface, dimensions and position, but the road pattern varies, and consequently the building orientation. In (c) and (d) the plots retain the same surface of (a) and (b), but their dimensions and position vary; new road patterns and EIP layouts are generated. (e) and (f) differ in plots' number, area, dimensions and position; the road pattern and EIP layout change accordingly.

These challenges contributed to perturbations of the parameters and the feasible region, resulting in instability of the Pareto set. The instability, on one side, has proved challenging for approximation and visualisation. On the other hand, the interactivity of the multidimensional visualisation of all the compliant layouts assisted the DMs to gain an insight into and promote learning for even ill-posed design spaces. The company DMs were motivated, in proactively contributing to the process, to maximise the revenues from properly planned and managed industrial symbioses.

Visual interaction with the set of generated layouts constituting the Pareto front is a promising method and tool to:

- improve the ratio of layouts considered satisfactory by DMs, within the large number of generated layouts, all compliant with the knowledge in the ontological formalisation and with the constraints;
- disregard the amount of generated layouts with minor variations in the parameters, the performance, and the characteristics, since they don't fit the improvement in one objective without impairing the value of other objectives.

9. Conclusion and future developments

9.1. Strengths of methodology and system

A novel generative approach of layouts was presented. The main strengths are in that it:

Contributes to ontology and knowledge reuse. A notable capability of ontologies is the reuse of existing knowledge. The present implementation has improved the effectiveness, since it has reduced the cost and the time required for the conceptualisation of specific domains compared to starting from scratch, and has increased the quality of newly implemented knowledge by reusing components that have already been validated by different research groups independently.

Contributes to ontology and knowledge sharing. "Ontology is another useful method to conceptualize the terms, their conceptual dependencies, and the associated axioms. Since it relies on meaning and rules to automate the information extraction and content analysis, it has been proved effective in avoiding the relatively opaque nature of machine learning" [152]. In layout planning and design, ontologies offer a methodology to conceptualize in a formal and explicit way a portion of experts' knowledge, which is compliant with Gruber's [5] classic definition of ontology as a "formal, explicit specification of a shared conceptualization". Knowledge sharing among machines, between humans and machine, and among humans, for instance to enhance, speed up and share the antecedents, the context conditions and the outcomes of each layout.

Separates the knowledge on the objects, the spatial relationships, and the constraints from the generative process. The knowledge has been successfully acquired from two existing domain ontologies. The knowledge has proved sufficiently general for the generation of layouts at different scales of planning and design. The specific domain of experimentation, the early stages of layout for an EIP, has proved suitable for both the domain knowledge and the process. Further general ontologies on AEC and Smart Cities (cf. 2.), and domain ontologies on EIP [153] are available and are candidates for integration in the system.

Strengthens the reuse of knowledge, and its scaffolding within and across domains. The acquisition and representation of knowledge are time and resource consuming activities; the present work demonstrates the feasibility of knowledge reuse in generative processes.

Demonstrates in a real-project the automatic generation of all the instances compliant with the knowledge. This was achieved by the increase and cost effectiveness of the computing power and the improvements in the reasoner engines. The tractability stems from the nature of the design process, the knowledge and the constraints. As considered in Section 8.2, they contribute to the stability of the Pareto set that is relevant for the decidability in the decision-making process. Sawaragi et al. [154] stated the necessary and the sufficient conditions for the stability as theorems: "If some simple technical conditions are satisfied, the stability of the Pareto frontier is provided by the coincidence of an unbiased Pareto frontier and a weak Pareto frontier. If the class of disturbances is broad enough, this condition is also necessary."

Offers a quick and effective tool to assist the early stages of planning and design. The integration of semantic generation with multiobjective decision analysis and interactive visualisation offers an efficient approach for stakeholders, planners, and designers to effectively explore large design spaces. During the decision-making process, they can address a larger number of options, under a wider range of objectives and criteria.

Enables learning, frequently layouts planning and design are man-in-loop processes, which are influenced by DMs' attitude, experience and context. Humans learn, if they have motivations to. These preconditions suggest that the decision-making process is undermined by uncertainties and no certain layout exists for a multiobjective problem to satisfy the requirements of the DMs definitely [155]. In the proposed approach, the visual interaction assists the users to explore the design space, starting from the Pareto front, learning from the relationships between layouts objectives and criteria. Cajot et al. [156] has argued that DMs' aim is to acquire a correct understanding of the design space, functional to interpret and contextualise the decisions: "Therefore, the insights gained during the process, about the tradeoffs, synergies and feasible boundaries are eventually more useful outcomes than the solution itself."

Rewards DMs with the exploration of the Pareto set, since they can gain awareness of having explored a larger number of options, and that can lead to an increase in the robustness of the chosen solution/s.

9.2. Gaps, challenges and outlooks

Ontology and knowledge reuse. The approach used, for the reuse of the ontologies and the integration of the existing knowledge, is manual. An automatic or assisted one would be beneficial, to acquire more existing ontologies (cf. 1.). Methodologies have been already put forward: authors of new ontologies can adhere to standards, developed for the collaborative exchange and reuse of ontology content [157]; KADS [158] advances ready-made model elements to assist the knowledge engineer in modelling a knowledge domain; Lonsdale et al. [159] propose architectures for automating ontology generation from existing ontologies. Towards implementation of ontology reuse, OWL 2 natively supports the axiom owl:imports. However, it manages an ontology as a whole, not allowing the custom import of classes, subclasses, relationships, or data properties. Solutions are being advanced either by linking back the reused concepts to the upper ontology with the annotation property "rdfs:isDefinedBy" or by declaring the reused classes and properties with OPLa, which is fully specified in OWL, and "models how ontology concepts can be grouped into modules, and the provenance of and interrelations between such modules" [160].

Ontology and knowledge sharing. Formal ontology languages (cf. 6.) should be used in writing ontologies, to achieve the formal and explicit specification of the conceptualisation. Formal and explicit conceptualisation is an expert intensive task, and tends to be time consuming and to be inefficient, due to the large expert effort required. Besides, a degree of generalisation is required, since an ontology describes general knowledge rather than a personal one. This is relevant for what an ontology is for: improving knowledge sharing and reuse; it can make the effort worthwhile.

One more objective or criterion. In real projects, there is always one (at least) missing objective or criterion to be added to the generative process. Furthermore, not all DMs may agree on criteria to place at the centre of the decision-making process, i.e. quantitative and qualitative evaluations.

A bunch of solutions is not welcome! DMs are used to asking a designer for a layout that matches their requirements. Providing instead a bunch of layouts, even if optimal, may simply dissatisfy them.

A bunch of solutions is frustrating! When the number of alternatives does not allow a (satisfactory) compromise to be achieved or, even, when the perception of the number of existing alternatives contributes to developing the awareness that no personally satisfying solution can be achieved (for instance because of the trade-off with other criteria or of other DMs' objectives) DMs may perceive the process as unsatisfactory, regardless of the extent of the gains they were actually able to achieve.

The quality of layouts is not apparent. Hou and Stouffs' research [92] aims to "improve design satisfaction": they advance search heuristics, including trial-and-error, backtracking and backjumping, that "shows a significantly superior performance of this advanced design grammar, which generates a substantial ratio of good designs, even including many perfect layouts." Our approach generates all the layouts, compliant with the knowledge. In that sense, it defines "a language of designs" [1] which, interpreted by a design machine (cf. 7.), generates only the formally valid layouts. They are formally valid, since OWL DL reasoner checks the consistency of the classes and relationships in the ontologies. That is to define the 'formal' quality of the generated layouts. Regarding the 'perceived' quality, it is much more dependent on DMs', planners', and designers' expectation or judgement:

> "there seems to be an inherent contradiction between the automation of problem solving here presented and design exploration. Whereas the latter is well adopted, the former is much less so. This is evident in the fact that systems that generate layouts never reached a widespread application. Essentially, full automation requires all the information to be explicated which means we have to provide the means to solve all the possible problems during the process. However, design exploration, regardless of manual or automated design, is always accompanied by some uncertainty and ambiguity as a designer cannot predict and describe all the situations, instead, he or she has to solve an issue after it emerges." [92].

DMs are plural, usually. In most AEC and Smart City projects several stakeholders bring their agenda into the process. The current access to the system is assisted: facilitator explains the methodology implemented in the system, accompanies the users along the process, interacts with the visualisation, and discusses the evidences from relationships across the layouts, the objectives, and the criteria. The experience and the communicative skills of the facilitator are of paramount relevance for the process. Some DMs would like to have direct access and insight to the system, to explore the design space and the Pareto front autonomously.

9.3. Future developments

Direct access to the system is the matter of implementing a web interface to the system, to grant personal access to DMs. At the same time, it is more than this, it deals on how the process has to develop in order "to facilitate informative discussion and team decision making" [161]. This relates to the very nature of the decision-making process, and stems from the number of the DMs involved, their priorities, motivations, expectations, skills and benefits. To some extent, "challenges involve irreducible uncertainty, heterogeneity of values, nonlinear dynamics, and contested problem framings [162]. With contested framings, parties to a decision disagree not just on potential solutions, but on the nature of the problem they are trying to solve." [163].

Researchers have explored the domains of multiobjective problems and multi-DMs participation, and have advanced several methodologies. Anderson-Cook and Lu [161] have discussed different visualisation techniques of Pareto fronts to match simultaneously multiple responses, e.g. plots of frequency of appearance on the Pareto front and mixture plots for showing the average frequency as optimal across the preferred desirability weight region for top ranked solutions. Furthermore, they have considered proportion plots to highlight top choices across all possible weight combinations in a set of decisions. Babbar-Sebens et al. [164] have proposed multi-user participation through interactivity: DMs' ratings are aggregated into a common preference model. To assist DMs to learn about a problem, Cajot et al. [156] have developed and tested interactive optimisation methods with parallel coordinates to "handle and visualize many objectives simultaneously, provide optimal solutions quickly and representatively, all while remaining simple and intuitive to use and understand by practitioners." Do Nascimento and Eades [165] have studied DMs' competition and cooperation in developing new solutions, and have proposed mechanisms to share the best performing solutions from personal searches among a group of users.

This body of studies contributes to shaping the framework for the future developments of the system.

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