Computing Narratives of Cognitive User Experience for Building Design Analysis

KR for Industry Scale Computer-Aided Architecture Design

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Abstract

We present a cognitive design assistance system equipped with analytical capabilities aimed at anticipating architectural building design performance with respect to people-centred functional design goals. The paper focuses on the system capability to generate *narratives of visuo-locomotive user experience* from digital computer-aided architecture design (CAAD) models. The system is based on an underlying declarative narrative representation and computation framework pertaining to conceptual, geometric, and qualitative spatial knowledge. The semantics of the declarative narrative model, i.e., the overall representation and computation model, is founded on: (**a**) conceptual knowledge formalised in an OWL ontology; (**b**) a general spatial representation and reasoning engine implemented in constraint logic programming; and (**c**) a declaratively encoded (narrative) construction process (based on search over graph structures) implemented in answer-set programming.

We emphasise and demonstrate: complete system implementation, scalability, and robust performance & integration with industry-scale architecture industry tools (e.g., Revit, ArchiCAD) & standards (BIM, IFC).

MOTIVATION

Professional planners, designers, engineers, and architects are required to imagine and anticipate user experiences and requirements given a *design*;[1] designers embed these aspects into their designs typically via an iterative refinement process that is primarily driven by creativity, heuristics, and interdisciplinary domain expertise. Whilst achieving the correspondence between physical (design) *structure and function*, architects go through a process of creative visuo-spatial abstraction, design conceptualisation, and the translation of an abstract specification into a concrete product that can be built in the physical world. In doing so, the architect must adopt and anticipate the perspective of a range of possible stakeholders, people groups, and situations, e.g., regular users, users with special needs (blindness, wheel-chair access, elderly), children, fire-fighters, and emergency situations. Put simply, the architect is confronted with the task to produce an elaborate human-centred description of the *perceptual* and *locomotive experience* of the users of the building being designed.

Contemporary CAAD Technology A Computer-Aided Architecture Design (CAAD) model consists of a detailed 3D description of a physical environment. Built on basic geometric primitives such as *point, line-segments, and polygons*, professionally designed CAAD models produced using contemporary design tools such as ArchiCAD and Autodesk consist of an elaborate specification sufficiently suited for civil engineering and product deployment tasks, e.g., involving ensuring structural consistency, advanced building simulation of aspects such as energy, air-flow, and cost-estimation.

Within architectural computing, recent years have witnessed the development of novel forms of representational and computational paradigms, also inherently geometrically-driven, such as parametric and generative design. However, what CAAD models and advanced structural engineering and simulation methods lack is a human-centred, semantic perspective of the design. In essence, within state of the art CAAD technology, the design conception, semantic modelling, and design communication (e.g., by 3D visualization) modalities have continued to retain their essential engineering-centred "*geometric*" character over the years.

Next-Generation CAAD Next-generation people-centred design *systems, frameworks, assistive tools, educational aids, and design policies* necessitate foundational abstraction and computational building blocks where the modalities of human perception, action, environmental experience, and design conception and semantics are central. Our research in this context addresses the following questions:

Q1. Contemporary computer-aided architecture design (CAAD) tools provide robust geometric modeling and structural engineering methods; how can the future evolution of (architectural) design computing bring notions of design semantics, structure, function, and people-centred design to the fore at an ontological, representational and computational level?

Q2. What is the role of specialized forms of visuo-spatial perception, abstraction, and commonsense spatial reasoning,

[1] By design, we refer to spatial design in general, and building architecture design in particular. By conventional design systems, we mean computer-aided architectural design (CAAD) tools.

within the broader realm of design computing, spatial design assistance, and tools for design learning and education?

Q3. What is the nature and form of the analytical feedback that designers and planners expect during the early design conception and iterative refinement phase? What are the implications of this from the viewpoint of the usability, interface, and human-computer interaction design aspects of architectural design (assistance) systems?

From the viewpoint of (Q1–Q3), the particular emphasis of our research has been on investigating the in-roads from the field of KR as foundational technologies within next-generation CAAD systems. Our perspective on artificial intelligence (AI) for (architecture) design is founded on the articulation of the *Science of Design* by Herbert Simon, and with Simon's interpretation of design as a "*decision-making process under constraints of physics, logic, and cognition*" (Baldwin, 2007). This view of the scientific design process underlies much of what artificial intelligence has to offer by way of its formal representational and computational apparatus to the domain of design computing.[2]

Cognitive CAAD Our basic proposition is that the foundational informatics of (architecture) design systems, tools, and assistive analytical aids concerned with creative spatial design and engineering tasks should also be based on modalities of visual and spatial cognition at the scale of everyday human perception and thinking. Toward this end, we propose that *design semantics, commonsense spatial reasoning and cognition*, and *visuo-spatial abstraction and computing* should be the driving forces underlying the foundations of next-generation design computing systems and paradigms. Next-generation CAAD should approach architecture computing from the perspective of *spatial informatics*, and appeal to *space* at the scale of everyday human perception and thinking in the context of *spatial cognition* (Bhatt, Schultz, and Freksa, 2013).

Our research addresses the representation of *space* from a formal modelling and computational viewpoint, i.e., *space*, as it is interpreted within the computer science disciplines concerned with the investigation of artificial intelligence and knowledge representation in general, and logic-based geometric and spatial representation and reasoning in particular (Bhatt et al., 2011). This field report focusses on the KR-specific aspects in the backdrop of system components concerned with design knowledge abstraction, representation, and reasoning. This report elaborates on (F1–F5):

[2] In recent years, several interdisciplinary initiatives comprising of computer scientists, engineers, psychologists, and designers have addressed the application of artificial intelligence techniques for solving problems that accrue at several stages of the design process: design creativity and conceptualization, functionality specification, geometric modelling, structural consistency & code-checking, optimization, collaborative (design) workflow management, and a plethora of other issues. The journal "Artificial Intelligence for Engineering Design, Analysis and Manufacturing" completed two decades of publishing in 2007 and its anniversary publication is a good overview of the area (Brown, 2007; Gero, 2007). A sketch of '*40 years of design research*' is available in (Bayazit, 2004).

I. Scope — Architecture Design

F1. *professional architectural design* as a function-driven iterative refinement process involving the structuring of *empty space*

F2. the *structuring of empty space* by an architect as being driven by the anticipation of visuo-spatial and locomotive user experience of people in built-up space (and in different situations)

II. Methods — AI for Design Computing

F3. the need for next-generation design tools and frameworks to regard human-centred modalities of *visuo-spatial perception and cognition* as being central;

F4. with respect to the "design as problem solving" paradigm of Simon (Simon, 1969, 1996), the development of artificial intelligence and spatial cognition & computation driven people-centred *analytical design computing* foundations for next-generation design systems

III. Demonstration — Declarative Narrativisation

F5. the computational *narrativisation of user experience* by way of declaratively modelled analytical descriptions of user experience externalised using natural language. This serves as: (1) a concrete example of our concept for KR for next-generation design computing foundations; and (2) a narrative-based *cognitivity benchmark* for qualitatively evaluating the functionality of our people-centred analytical design computing framework.

The paper presents an overview of the overall cognitive design assistance system, whilst emphasising:

- the underlying (general) declarative techniques for commonsense conceptual and qualitative spatial representation and reasoning rooted in methods such as formal ontology and description logics, constraint logic programming, and answer-set programming (Gelfond and Lifschitz, 1988; Baral, 2003); and
- the system capability to generate *narratives of cognitive user experience* based on the underlying KR-driven model and implementation as a model for next-generation people-centred analytical design computing foundations.

The paper illustrates case-studies and results obtained from a fully implemented system. The case-study focusses on *narratives of user experience* in the Museum Calouste Gulbenkian in Lisbon, Portugal. However, we emphasise that the narrative generation capability is functional for any digital model of a building that conforms to architecture industry standards, namely, the Building Information Model (BIM) (Eastman et al., 2008) and Industry Foundation Classes (IFC) (Froese et al., 1999). In this context, we also provide empirical results about the performance of the computational framework, focussing on the core design analysis algorithms and graph search processes implemented in answer set programming.

NARRATIVE AND DESIGN COGNITION

A *narrative* in its most general (dictionary definition) form corresponds to "*a spoken or written account of connected*

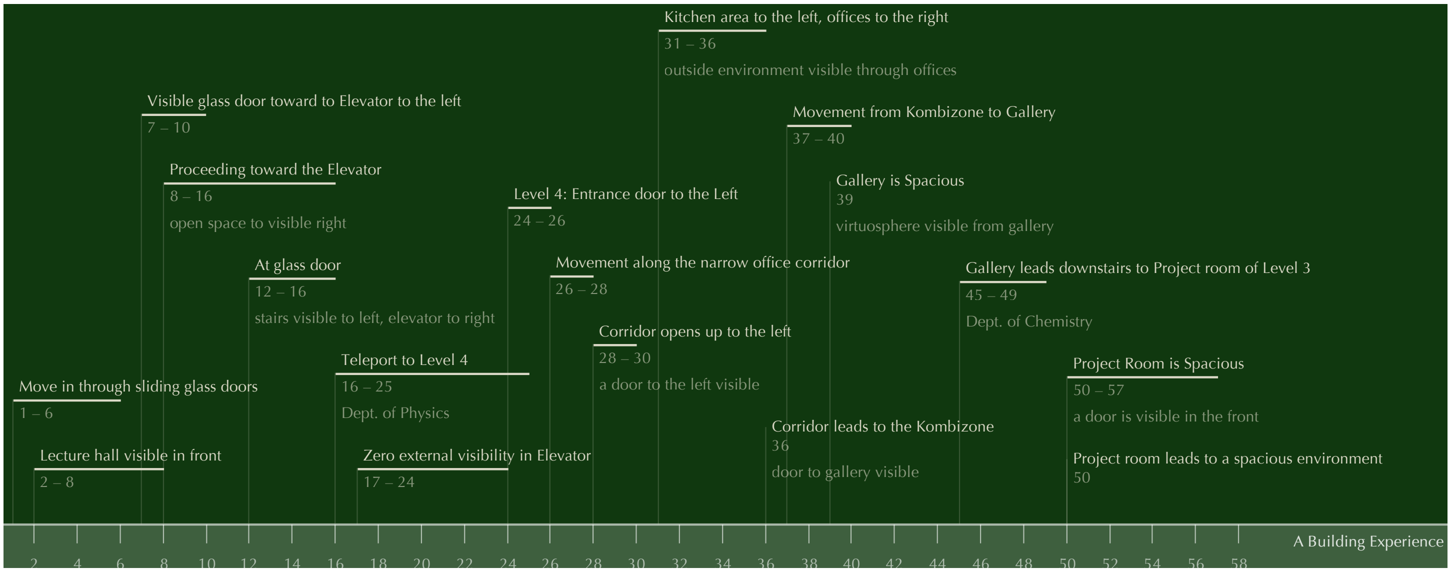


Figure 1: A Visuo-Locomotive Building Experience

events; a story". Narratives serve a crucial role in everyday human perception and cognition; narrativisation of everyday perceptions by humans, and the significance of narratives in communication, interaction, and belief formation has been investigated under several frameworks, e.g., discourse analysis and narratology (Herman, Jahn, and Ryan, 2005), the narrative paradigm (Fisher, 1987), and through several other interdisciplinary initiatives involving the arts, humanities, and natural sciences. Most recently, the trinity of logic, language, and computer science has begun nurturing the field of "*computational models of narratives*" (Mani, 2012; Finlayson et al., 2013). To understand the nature of narratives from the viewpoint of the research presented in this paper, consider the following task:

> **Moving around in a building**. You enter a building (e.g., a museum, or air-port), possibly for the first time; as you walk around, guided by its internal structure, you (are required to) form and record your experience based on visuo-spatial, locomotive, and environmental affordance-based perceptions in the building.

Given the objective to externalise the observed perceptions in the building as required above, a human subject would be able to achieve the task using a range of modalities grounded in language, diagrams, schematisations etc. The experience may be described using a range of descriptive modalities such as written or spoken natural language (e.g., involving expressive motion, path, and qualitative spatio-linguistic predicates), diagrammatic representations (e.g., sequence graphs, bubble diagrams, schematisations of the environment), wayfinding experience (rotation or turn actions performed, getting lost) etc. For instance, a natural language description of the experience could be as follows (Fig. 1):

> **A Narrative of user experience**. As you move in through the passage of the sliding doors, you see a circular lecture hall directly in front through the glass panel, the elevator on the left...Exiting the elevator on Level four, there is a door to the left, leading up to a long, narrow corridor with an sequence of offices on the right...

Basically, human cognitive processes concerned with perceptual information processing would be able to conceptualise and externalise *a story* —linguistic or otherwise– that reports the building experience with relative ease; a large-scale experiment —typical in the field of environmental psychology (Bechtel and Churchman, 2002)— with many subjects would serve as a good reflection of the collective narrative of user experience in the environment under consideration; Fig. 1 presents one example of such an aggregate qualitative description of the experience of users in a given building. Architects concerned with designing a building are confronted with *imagining and anticipating* the perceptual experience of building users during the initial (design) conception phase, at a time when all that exists is *empty space* (Fig. 3(a), and 3(g)). In general, architects must envision the cognitive experiences of a range of people / user groups in different situations (in addition to externalising their own specialist analyses on functional design performance, and creative & aesthetic preferences).

Assistive design computing systems that can —based on an underlying formal representation and reasoning apparatus— generate narratives of user experience with the descriptive complexity of an architect or a user of a building are therefore needed, and can serve a good developmental benchmark. Methodologically, the objective of such systems is to provide high-level, semantic, analytical design computing capabilities aimed at assisting the architect or designer in a function-driven creative design task.

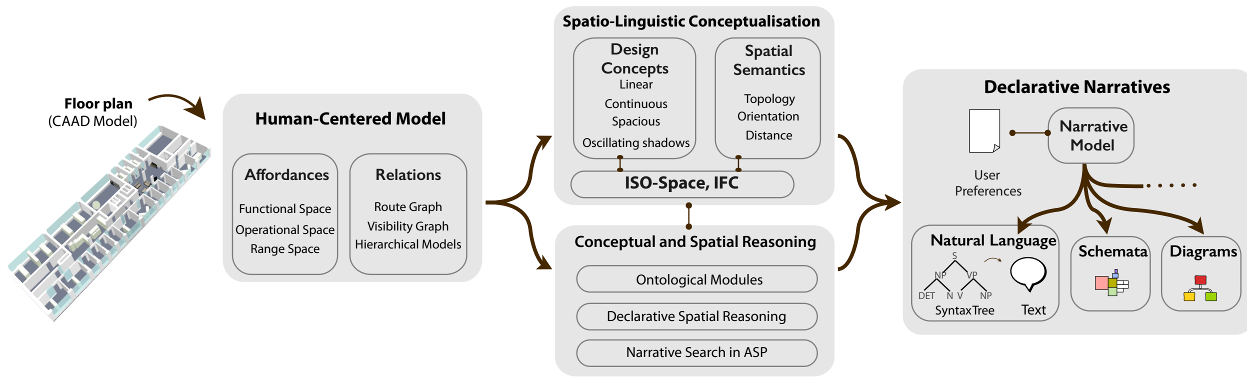


Figure 2: Reverse Engineering CAAD: Overview of Declarative Narrativisation Process

In this paper, we use the framework of narratives to report on a set of KR-driven *analytical design computing* capabilities concerned with providing decision-support to an architect or planner. Our design assistance system is able to compute narratives of user experience solely from geometric CAAD models or building master plans. Our long-term goal is to achieve a level of analytical accuracy, and semantic and descriptive quality and expressibility that is comparable with the performance of specialist designers, and novice users of buildings – this guides our broad-based work on computational narratives for KR-driven architectural design computing & cognition.

Computing Narratives

We adopt the conceptual framework of *narratives*, and specialise it for computing declarative narratives directly from 3D CAAD models of built-up spaces; this is akin to *cognitively-driven reverse engineering of CAAD models*. The semantic information that is obtainable from the computed narratives of user experience consist of visuo-spatial, locomotive, and affordance-based analytical content conforming to qualitative, spatio-linguistic conceptualisations pertaining to built-up spaces in the minds of people – both specialist architects, as well as potential users of a building.

Declarative Narrativisation Descriptions of user experience in buildings, e.g., in the form of a linguistic narrative, may be human-generated, or they could be generated by a system or suite of algorithms:

1 *Human-Generated Narratives*. Listing 1 (Fig. 4) depicts an example of the kind of natural language description that a human user may generate. The descriptions are representative of a user experience recording in an existing public building. We refer to the descriptions in Listing 1 as "*narratives of user experience*".

2 *System Generated Narratives*. Listings 2 (Fig. 4) is an example of computationally generated narratives of user experience — these have been generated solely on the basis of an elaborate 3D geometric CAAD model (of a real museum building). We refer to the formal knowledge structures and models from which such (linguistic or other) analytical descriptions of user experience can be generated as "*declarative narratives of user experience*". We refer to the process of computationally generating the formally characterised declarative narratives as *declarative narrativisation*.

Why Declarative? The declarative-ness (of narrativisation) signifies the existence of models that can be reasoned and queried upon, e.g., within a traditional declarative KR framework such as logic programming, constraint logic programming, description logic based reasoning, answer-set programming, and even other commonsense reasoners based on expressive action description languages.

The Declarative Narrativisation Framework

Figure 2 presents a conceptual overview of the narrativisation framework, system components, and the steps leading up to the computation of the declarative narratives, and the generation of language as a way to materialise the analytical information contained in the declarative narratives. Core components (NF1–NF3) are elaborated in the following:

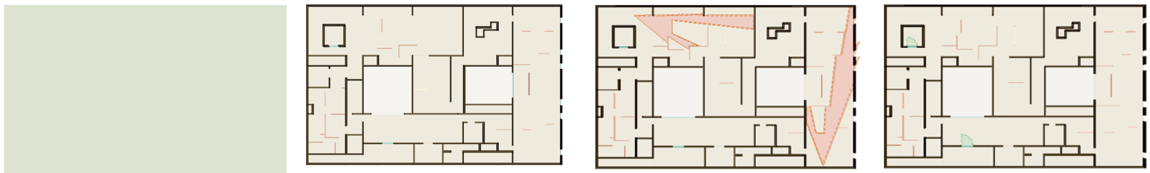
NF1. People-Centered Design Typology Affordance spaces are spatial entities whose geometric extensions in space are derivable from the other (explicitly defined) material objects (e.g., door, wall, furniture; Fig. 3(b)), or their attributes, e.g., the opening space of a door can be computed from basic parameters of the door itself. Affordance spaces are derived from the abstracted shape geometries of physical objects chiefly using (a) polygonal boolean operations (intersection, difference, union) (Lauther, 1988), (b) line-of-sight calculations (Asano et al., 1985), and Minkowski sum (Kaul, O'Connor, and Srinivasan, 1992):

A1. *Movement Spaces*. Union of navigable surfaces (e.g. slabs) subtracted by obstacles such as walls (Fig. 3(f)).

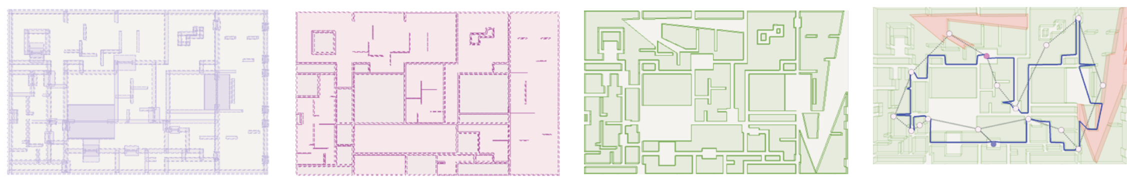
A2. *Range Spaces*. Point-visibility polygons (isovist) restricted to the sensor's angular field of view and focus distance (Fig. 3(c)).

A3. *Operational Spaces*. Sweeping, extruding, translating, rotating, and scaling parts of the physical geometry of the reference object (e.g. sweeping a door panel; Fig 3(d)).

A4. *Functional Spaces*. Buffer of the physical geometry of the reference object subtracted by obstacles (Fig. 3(e)).



(a) Open Space (i.e., no design exists) (b) A CAAD model (input) (c) Range Space (visual, or sensory) (d) Operational Space of doors



(e) Functional Space of walls, and doors (walls are disabled) (f) Movement Space (walls are disabled) (g) Structured 'Empty Space' (i.e., truly non-interfering space having subtracted (b-e)) (h) Route Graph (logical connectedness), and Route Path (i.e., with special properties)

Figure 3: Structuring Empty Space. Illustrated using the derivations computed by our design analysis engine.
Floor plan: *Museum Calouste Gulbenkian, Lisbon, Portugal*.

Listing 1. Human Generated User Experience (Gaizauskas et al., 2012): (1) The main entrance to the building is located in a corner under an overhang, which does not allow it to be visible to patients easily. (5) The immediate interior area around the entrance feels reassuring because it is open and airy. (11) Most of the windows in the consultation rooms overlook the courtyards. (18) [The] space behind the sculpture could be used for outdoor seating in the summer and passers-by would be able to see that there was a cafe available in the area.

Listing 2. System Computed Specialist Analysis: The layout and spatial organisation of the museum maintains 'continuity' between locations. The overall plan follows a circular structure, starting at the front lobby, passing through Rooms A, B, C, D, and via the North Door of Room E. The rooms flow linearly, and maintain visibility with the external environment (except during the segment between Room C and Room D). By removing Wall Y in Room X, the circular ring structure can be converted to a hierarchical structure with Room Z as the central hub. Direct sunlight exposure is achieved in approximately 85% of the floor plan. Region X never receives any sunlight at anytime during the year.

Figure 4: Extracts of (1) human narratives about buildings (Gaizauskas et al., 2012), and (2) System Computed Narratives from a CAAD model of the Museum Calouste Gulbenkian, Lisbon, Portugal

A5. *Empty Spaces*. Union of movement spaces subtracted by other affordance spaces such as functional and range spaces spaces (Fig. 3(g)).

A6. *Route Graph*. Connectivity relations are intersections between movement spaces and waypoints (e.g. doors). Actual route paths provide precise co-ordinates of motion along a route (Fig. 3(h)).

A7. *Visibility Graph*. Visibility relations are intersections between visibility spaces and objects (Fig. 6(c))

The spatial design typology in (A1–A7) provides a basis to further analyse and "make sense" of the "*shape of the empty*" (Bhatt, Schultz, and Huang, 2012) that results from a configuration of a designed structure as available within a CAAD model. This is done by establishing a formal link between low-level physical design structure, and high-level conceptualisation of design function as identifiable by the spatio-linguistic conceptualisation of architects, i.e., by formalising modelling and reasoning about design semantics.

NF2. Design Semantics and Ontology Whereas the philosophy of *form and function* in design is a well-studied topic, the formal modelling of *structural form* and resulting *artefactual function* within design assistance systems remains elusive. We make these definitions explicit by ontologically modelling architectural domain entities, and their properties and related constraints. We interpret "(structural) form" and "(artefactual) function" by specifying modular ontologies and their interplay for the architectural design domain.

Multi-Perspective Semantics and Modularity. Consider the illustration in Fig. 5: an abstraction such as a Room or Wall may be identified semantically by its placement within an ontological hierarchy and its relationships with other conceptual categories. These different categories are used by a designer during the initial design conceptualisation phase. However, when a design is implemented in a CAAD tool, the same concepts acquire a new perspective, i.e., the designer has to interpret design concepts in terms of points, line-segments, polygons and other geometric primitives available by the design tool. Given the lack of design semantics within contemporary design tools, no solution is available for a knowledge-based system to make inferences about the conceptual design and its geometric interpretation within a CAAD model in a unified manner. Our approach is to model these perspectives and their respective spatial semantics by using modular ontologies that individually comply with one of the perspectives. Presently, we represent conceptual, qualitative, and quantitative ontological modules using the Web Ontology Language (OWL). These modularly specified ontologies not only reflect the thematically different perspectives in a more adequate way but they also provide a clear ontological representation of the interplay and exchange between form and function, and underlying spatial constraints. This also directly supports modular conceptual and spatial reasoning (M1-M3):

M1. *Conceptual Space* This ontological module reflects terminological information of architectural entities. Here, the entities are regarded as such, i.e., they are defined according to their properties without taking into account the context in which they are put. The concept space is based on DOLCE (Masolo et al., 2003), in particular, on the OWL version DOLCE-Lite[3]. For instance, the class construction below specifies that types of buildings, e.g., courthouse, museum or university, are non-physical endurants that depend on an actual (physical) building, which provides the building's type or function:

$$\mathsf{BuildingType} \sqsubseteq \mathsf{dolceLite{:}non\text{-}physical\text{-}endurant} \\ \sqcap \exists\, \mathsf{dolceLite{:}generically\text{-}dependent\text{-}on} \,.\, \mathsf{PhysicalBuilding}$$

Module M1 defines other similar constructs that occur in the design domain, such as VisualSensor, SlidingDoor, LandingSpace, OpenFloor.

M2. *Quality Space* This ontological module reflects qualitative spatial information of architectural entities. In particular, the module uses relations as provided by the topological spatial calculus RCC-8 (Randell, Cui, and Cohn, 1992), and calculi pertaining to other aspects of space. Qualitative spatial relations provide an abstraction method for specifying high-level design knowledge, e.g., a Room is necessarily a *proper part* of a Building. For instance, the category OpSpaceDoor specifies the region that is composed by a door and its opening angle, the category OpSpaceWall specifies the region that is composed by the external boundary of a wall, and the category OpSpaceWindow specifies the region that is composed by a windows and its opening angle.

$$\begin{aligned} \mathsf{OpSpaceDoor} &= \langle \mathsf{has\_operational\_space} \rangle^{M2}\, \mathsf{Door} \\ \mathsf{OpSpaceWall} &= \langle \mathit{has\_operational\_space} \rangle^{M2}\, \mathsf{Wall} \\ \mathsf{OpSpaceWindow} &= \langle \mathit{has\_operational\_space} \rangle^{M2}\, \mathsf{Window} \end{aligned}$$

The following constraint encodes the requirement that all doors have to be externally connected (EC) with doors, walls, or windows:

$$EC(\mathsf{OpSpaceDoor},\ \sqcup\ \mathsf{OpSpaceWall}\ \sqcup\ \mathsf{OpSpaceWindow})$$

M3. *Quantity Space* This ontological module reflects geometric information of architectural entities. It is closely related to the Industry Foundation Class (IFC) data model (Liebich et al., 2006) and partially mirrors the IFC classes; IFC consists of a non-proprietary data model and exchange format to foster interoperability in the building industry.[4] For example, Door, Wall, and Window are characterized together with their properties length, orientation, placement.

$$\mathsf{Door} \sqsubseteq \mathsf{StructuralBuildingElement} \sqcap =1\ \mathsf{openingAngle} \,.\, \mathsf{float} \\ \sqcap =1\ \mathsf{doorknobType} \,.\, \mathsf{ENTITY} \sqcap =1\ \mathsf{height} \,.\, \mathsf{float} \\ \sqcap =1\ \mathsf{length} \,.\, \mathsf{float} \sqcap =1\ \mathsf{width} \,.\, \mathsf{float}$$

Data provided by IFC for a concrete building model can then be instantiated with respect to the quantity space ontological module.

Integrated Representation The connection of the three different modules (M1–M3) results in formalizing *link relations* across modules.[5] For example, an instance of Wall from the quantity space is related to an instance of Wall from the quality space, or as a physical endurant in the conceptual space. In the quantitative module, it is described by its length and position, while its counterpart in the qualitative module defines region-based relations to other walls and relations to rooms it constitutes.

Reasoning with Intergated Representation An important conceptual reasoning task in the design context is to determine whether or not a set of conceptual requirement constraints specified by a designer may possibly have a model.

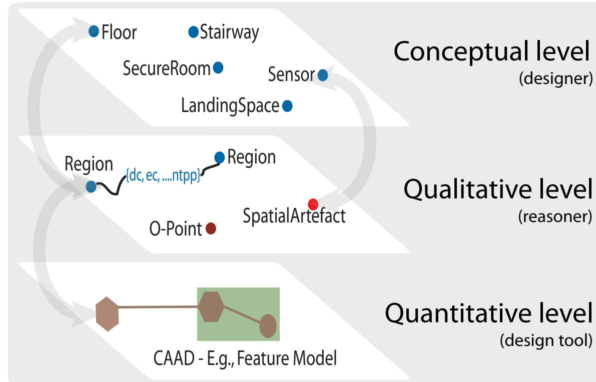
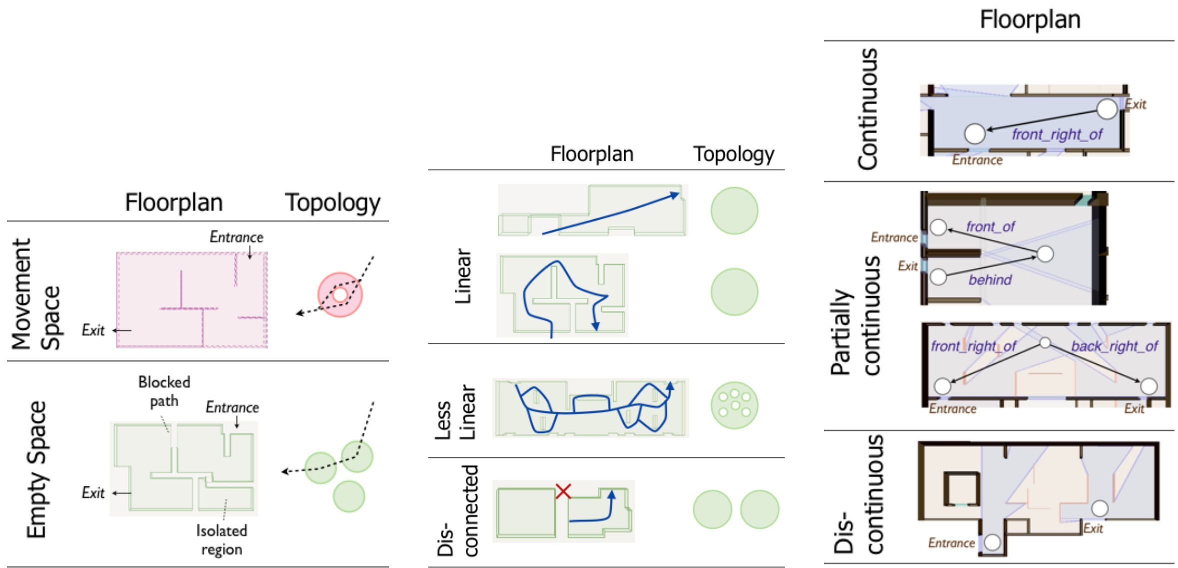


Figure 5: Multi-Perspective Semantics and Ontological Modularity

[3]DOLCE-Lite. `http://www.loa-cnr.it/ontologies/DOLCE-Lite.owl`

[4]IFC is based on object classes, e.g., *IfcWall* or *IfcWindow*, and their relationships containing metrical data as properties. We apply the stable release IFC2x3 TC1 (Liebich et al., 2006) defining 653 *building entities* (e.g., *IfcWall*) and additionally, several *defined types*, *enumerations*, and *select types* for specifying their properties and relationships.

[5]Bhatt, Hois, and Kutz (2012) provides technical details concerning the implementation of ontological modules using the framework of $\mathcal{E}$-Connections (Kutz et al., 2004). For the purposes of this paper, it suffices to think of link relations as predicates that link categories from respective modules; these links are utilised in a logic programming environment in order to assimilate knowledge from different perspectives within the body of inference rules in the logic program.



(a) Affordance path analysis can identify design malfunctions.

(b) Empty space topology indicates the linearity of a space.

(c) Visibility of landmarks indicated visual continuity

Figure 6: Affordance Paths, and Navigation Linearity and Visual Continuity

This form of reasoning is useful to check if a given set of design requirements are mutually consistent from the viewpoint of a conceptual specification; this kind of reasoning is directly possible with state of the art *Description Logic* (DL) (Baader et al., 2003) based reasoning systems such as RACER (Haarslev, Möller, and Wessel, 2004), PELLET (Sirin et al., 2007). With respect to the semantics of geometric and qualitative spatial knowledge, we have developed the CLP(QS), which is a declarative spatial reasoning system capable of modelling and reasoning about qualitative spatial relations pertaining to multiple spatial domains, i.e., one or more aspects of space such as topology, and intrinsic and extrinsic orientation, distance (Bhatt, Lee, and Schultz, 2011; Schultz and Bhatt, 2012). CLP(QS) also offers mixed geometric-qualitative spatial reasoning capabilities, and in its current form, a limited of quantification support offering the means to go back from qualitative relations to the domain of precise quantitative information. CLP(QS) is implemented as a general library within the context of Constraint Logic Programming (CLP).

NF3. Spatio-Linguistic Conceptualisation & Reasoning Conceptual reasoning is hierarchical, deriving high-level design concepts from qualitative spatial relations based on low-level geometric primitives. Qualitative spatial representation and reasoning (QSR) provides a commonsensical interface to abstract and reason about quantitative spatial information. Qualitative spatial calculi are relational-algebraic systems pertaining to *topology, orientation, direction, size* (Cohn and Renz, 2007). Within computing for spatial design, the use of formal qualitative spatial calculi and conceptual design requirements serve as a link between the *structural form* of a design and the differing *functional capabilities* that it affords or leads to, e.g.:

C1. The FunctionalSpace of the Door of every Office should overlap with the RangeSpace of one or more Camera or MotionSensor.

C2. A MonitoredArea that are connected by doors and/or passages should not have any security blind spots whilst people transition from one room to another.

C3. Figure 6(a) illustrates an inconsistency with circulation: a physical path exists between two locations if MovementSpace topology is connected, however, when taking FunctionalSpaces of objects into account we find that there is no affordance path; the EmptySpace topology is disconnected.

Examples in (C1–C3) constitute the basic case; more complex requirements are driven by high-level spatio-linguistic patterns and features, e.g., OpenPath, Around, Along etc. The semantics of such spatio-linguistic conceptual information is grounded with respect to the ISO-Space standard, an emerging initiative concerned with formalising the semantics of the representation of motion as it is expressed in language, e.g., *path predicates* and *manner-of-motion-predicates*.[6]. Finally, concepts most closely related to the design concept of an expert architect often involved a mixture of spatial prepositions, and high-level spatial patterns. We present some examples of such design concepts by way of **(A–C)**:

A. *Linearity*. Navigation linearity is associated with the number of path decisions that a person needs to make as they move through a space (Stephen Bitgood, 1992). A room

[6]The formal semantics underlying the ISO-Space framework is in Dynamic Interval Temporal Logic (DITL) and qualitative spatial formalisms as conceived within the QSTR community (Mani and Pustejovsky, 2012)

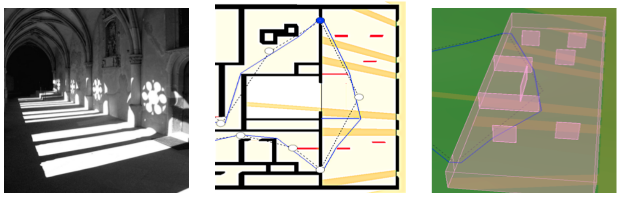


Figure 7: A Route through an Oscillating Shadow Pattern

is qualitatively *more linear* than another room if it has a less complex empty space topology, e.g., defined as having fewer regions with fewer holes (assuming that the rooms have the same number of entry and exit points). (Fig. 6(b))

B. *Visual Continuity*. Visual continuity through an environment is maintained if, as visitors move through the environment, they have visual contact with important waypoints (such as entrances, exits, or signage). (Fig. 6(c))

```
visual_continuity(discontinuous, id(LandmarkA), id(LandmarkB)):-
        visibility_space(id(LandmarkA),VisGeometryA),
        visibility_space(id(LandmarkB),VisGeometryB),
        topology(rcc8(dc), VisGeometryA, VisGeometryB).

visual_continuity(partial, id(LandmarkA), id(LandmarkB)) :-
        visibility_space(id(LandmarkA), VisGeometryA),
        visibility_space(id(LandmarkB), VisGeometryB),
        topology(rcc8(po), VisGeometryA, VisGeometryB).

visual_continuity(continuous, id(LandmarkA), id(LandmarkB)):-
        visibility_space(id(LandmarkA),VisGeometryA),
        physical_space(id(LandmarkB),PhyGeometryB),
        mereology(rcc5(pp), PhyGeometryB, VisGeometryA).
```

C. *Oscillating Patterns of Sunlight and Shadows*. The influence of sunlight (and resulting shadows) in evoking aesthetic impressions is well known in design (Seidler, 1959). For instance, one may identify an oscillating pattern of sunlight and shadows at a given time and place by determining whether the shadows in a room have a particular topology (Fig. 7):[7]

```
sunlight(oscillating_pattern, id(Room), id(Sun)) :-
         movement_space(id(Room),MvGeometry),
         sunlight(id(Sun),SunGeometry),
         SunPattern=intersection(MvGeometry,SunGeometry),
         enumerate(disconnected_regions, SunPattern, N), {N > 3}.
```

NF4. From Declarative Narratives, to Narratives of User Experience NF1–NF3 focussed on the semantic and spatial abstraction and reasoning methods that are used to generate people-cognition centred visuo-locomotive analytical information. The computed and inferentially derived analytical information is available declaratively, i.e., it is possible to query the analytical information using a combination of:

- conceptual reasoning with a DL reasoner such as Racer (Haarslev, Möller, and Wessel, 2004), Pellet (Sirin et al., 2007) (e.g., retrieval tasks)
- (system level) integration of conceptual reasoning with constraint logic based spatial reasoning and question-answering (in Prolog)

[7]It is straightforward to determine the sun location based on a given time, or the time that corresponds to a given geospatial location.

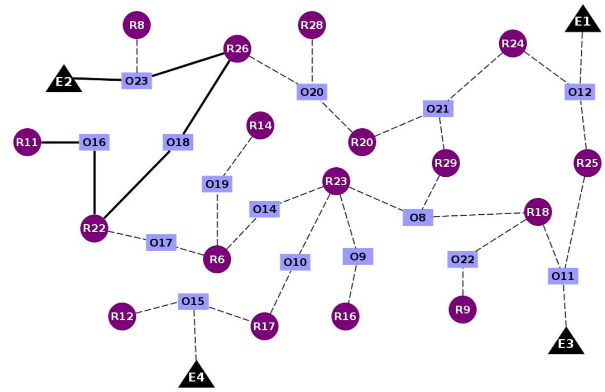


Figure 8: Route Computed by an ASP Solver

- application of answer set programming (Fig. 9) to search over the available analytical information, e.g., wrt. a graph search encoding, thereby computing stable models that satisfy certain design constraints fulfilling an anticipated "visuo-locomotive experience". For instance, a range of routes that fulfil particular user experience criteria may be computed: e.g., routes to a fire-exit (Fig. 8), nearest room from where sunset or sunrise are visible, routes that meet certain experiential constraints (e.g., visibility of at least one Bathroom, visibility to external environment)

The analytical information, in order to be useful to designers, has to be communicated using human-centred modalities; toward this, possible approaches are:

- *simulation*: diagnostic pin-pointing using virtual reality (VR) or similar visual techniques (e.g., 2D and 3D simulation)
- *schematisation*: generation of abstract schematisations, dynamic graph based complex spatio-temporal data visualisations, diagrams (e.g., similar to the timeline in Fig. 1)
- *stories in natural language and speech*: language generation based on the declarative analytical information, i.e., narratives of user experience

For the discussion in this paper, we focus on the use of the analytical declarative knowledge to generate spatio-linguistically grounded narratives of user experience (e.g., Listing 2 in Fig. 4). Template syntax trees for describing particular design concepts (e.g. referring to *linearity* as "the space flows linearly") are encoded, and instantiated with respect to the declarative narrative model.[8]

Empirical Performance Evaluation

The reported design analysis system and narrativisation framework have been fully implemented, and have also been used as a workbench for conducting experiments using real, industry-scale building data from CAAD models produced with commercial CAAD tools such as ArchiCAD and Autodesk Revit.

[8]We utilise the open source tools available via the Stanford Natural Language Processing Group: `http://nlp.stanford.edu/`

```
#const start = r11.
#const end = fireEx.

%%%%Domain of Rooms
objectClass(r0, cDsMovementSpace).
objectClass(r1, cDsMovementSpace).
objectClass(r2, cDsMovementSpace).
objectClass(r3, cDsMovementSpace). ...

%%%%Domain of Doors, Fire-Exits
objectClass(o0, dsHorizontalPassage).
objectClass(o1, dsHorizontalPassage).
objectClass(o2, dsHorizontalPassage).
objectClass(o3, dsHorizontalPassage). ...

connection(r6, o14). connection(r8, o23).
connection(r9, o22). connection(r6, o19).
connection(r6, o17). ...

edge(X, Y) :-
      connection(X, Y),
      objectClass(X, cDsMovementSpace),
      objectClass(Y, dsHorizontalPassage).
edge(X, end) :- connection(X, end).
edge(Y, X) :- edge(X, Y).

adj(X, Y) :- edge(X, Y).
adj(X, Y) :- adj(X, Z), adj(Z, Y), edge(X, Z).
:- not adj(start, end).
selected(X, Y) :- adj(X, Y), edge(X, Y), connection(X, Y).

#minimize[selected(X, Y)].
#hide.
#show selected/2.
```

Figure 9: Basic encoding for graph search as an answer set program (minimal example serving illustration purpose)

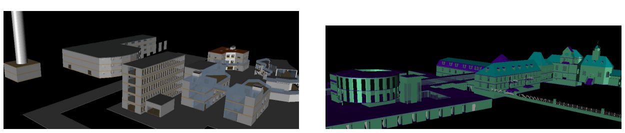


Figure 10: Select CAAD models used for empirical analyses – An Academic Interchange, and the Schloss Dagstuhl Palace

Datasets The dataset consists of 10 CAAD models of large-scale public environments of different sizes (e.g., an international academic interchange building (Germany), parts of the campus redevelopment plan at the University of Arkansa (USA), the Schloss Dagstuhl building(s), model of the Museum Calouste Gulbenkian (Portugal) etc (e.g., see Fig. 10).

Analysis The empirical analysis of the implemented system is performed for the following aspects (E1–E2):

E1. *Design Typology Computation*: Geometric computations are needed to compute the various affordance spaces as per the people-centred design typology.[9] The design typology computation experiments (Fig. 11) were conducted on a MacBookPro, OS X 10.6.8, 2.66 GHz with 4GB RAM. As can be seen Fig. 11, typology computations have been fine-tuned to suit practical applications demanding scalability for real-time performance; see (Schultz and Bhatt, 2013).

[9]Computing the *isovist* was done using the VisiLibity package (Obermeyer and Contributors, 2008). Polygon operations were performed using General-Polygon-Clipper., `www.cs.man.ac.uk/~toby/alan/software`

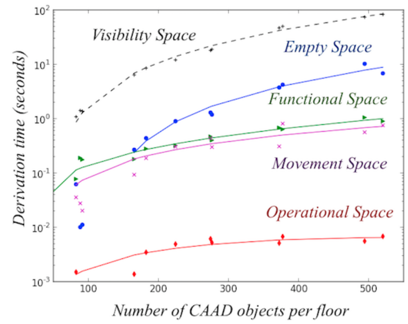


Figure 11: Time taken for Design Typology Computation

CAAD Model	Edges	Nodes	Grounding	Search
Gulbenkian	31	31	0.00	0.01
Flynn Interchange	32	30	0.00	0.01
Acad. Interchange (I)	90	86	0.03	0.36
Cartesium	150	148	0.13	9.68
AC11-Institute	161	161	0.15	4.58
Arkansas: Dining	188	179	0.19	82.13
Acad. Interchange (II)	215	208	0.16	18.17
Arkansas: Basketball	231	208	0.30	481.32
Arkansas: Football	243	227	0.39	315.93
Parkland Hospital	400	393	1.16	377.37

Table 1: *The average time (30 experiments per design) taken to compute shortest graph paths to simulate narrative generation*

E2. *Narrative Generation via a Search Process in ASP*: The derivation of the narrative of user experience that has been implemented using answer set programming is evaluated. The ASP based experiments (Table 1) were conducted on an iMac machine with 2.7GHz, with 8 GB RAM. At this stage, fine-tuning the domain encodings in ASP has not been a principal concern. However, we are presently investigating effective encodings in ASP that specifically target graph structures and dataset sizes that are typical in the computer aided design domain.

Conclusions

We have presented a system for declarative narrativisation of user experience in spatial design. In contrast to the strictly geometric-centric view of building information, our framework explicitly incorporates human-centered perceptual models in the form of affordances and visuo-spatial abstraction. We have conducted experiments using real, industry scale CAAD models using a full implemention of our framework. In the experiments, all human-centered affordance spaces were computed within a relatively short time, thus demonstrating the practicality of the narrativisation framework in real-world settings. In the future we plan to extend the affordances to include a broader range of design features, and to formally benchmark the system-generated narratives wrt. human-generated narratives.

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