The Shape of Empty Space

Human-Centred Cognitive Foundations in Computing for Spatial Design

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***Abstract*—**We propose a human-centred model for abstraction, modelling and computing in function-driven spatial design for architecture. The primitive entities of our design conception ontology and computing framework are driven by classic notions of 'structure, function, and affordance' in design, and are directly based on the fundamental human perceptual and analytical modalities of visual and locomotive exploration of space.

With an emphasis on design semantics, our model for spatial design marks a fundamental shift from contemporary modelling and computational foundations underlying engineering-centred computer aided design systems. We demonstrate the application of our model within a system for human-centred computational design analysis and simulation. We also illustrate the manner in which our design modelling and computing framework seamlessly builds on contemporary industry data modelling standards within the architecture and construction informatics communities.

I. Introduction

A Computer-Aided Architecture Design (CAAD) system, at its core from a modelling and information-theoretic viewpoint, consists of a standard range of geometric constructs involving points, line-segments, polygons, and other complex aggregates of basic geometric primitives. These primitives provide the fundamental foundation needed for the structural engineering of the physically built environment using digital means. Recent years have witnessed the development of novel forms of representational and computational paradigms, also inherently geometrically-driven, such as parametric and generative design (modelling and computing). In essence, within state of the art CAAD technology, the design conception, modelling, and design communication (e.g., by 3D visualization) modalities have continued to retain their essential engineering-centred "*geometric*" character over the years.

Architecture design is indeed about '*space*': empty space, spatial structures, and the process of structuring. Architects essentially organize empty space by building-up structures and artefacts of people's everyday existence. The process of architectural structuring transforms and organizes empty space into something of a desired *form* (e.g., a balanced or spacious room, a visually pleasing scene), *function* (e.g., easily navigable) and *semantic connotation* (e.g., of a 'place'). In achieving the correspondence between physical structure and function, architects go through a process of creative visuo-spatial abstraction, design conceptualisation, and the translation of an abstract design into a concrete product that can be built in the physical world. The entire design process, from design conception through engineering and deployment, goes through an iterative refinements cycle consisting of several stages where designers employ the creative and engineering facets of their profession [21].

The *design studio* experience, which is one of the oldest methods for architecture education, learning, and critique, relies principally on design sketches, early drawings, and 3D models at different levels of articulation and detail. The method has evolved and manifests itself beyond architecture schools into the professional realm as well.[1] When one examines the products of *design thought* during a creative spatial design task (e.g., a studio-based *desk crit* or during the early design conception phase in professional design), the visuo-spatially driven human-centred nature of the design constructs is evident. Designers invariably rely on two fundamental modalities, namely, *visibility* and *motion*, by which humans perceive and experience the surrounding *space*. As an illustration, consider the following diverse spatial design scenarios (also respectively illustrated in Fig. 1):

S1. A Museum Design Task.

▷ *Continuity of perception*. The layout and spatial organisation of the reception area of the museum should maintain a sense of 'continuity' between locations. Continuity may be thought of as mutual visibility or reachability amongst a set of locations.

S2. University Campus Planning.

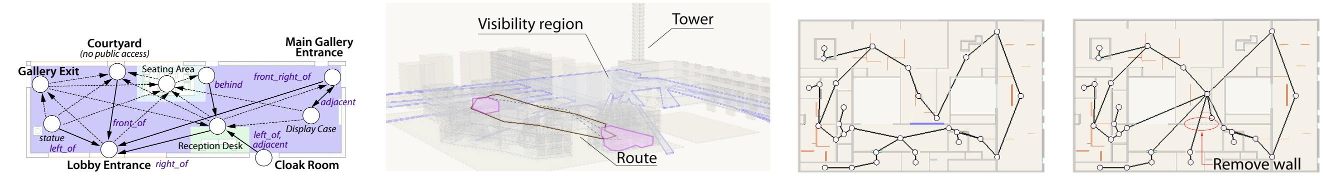
▷ *Visibility and navigation*. Going from the eastern to the western end of the new campus, certain landmarks should be visible so as to offer a point of reference or localisation at all times.

S3. Indoor Navigation Planning.

▷ *Circulation pattern analysis*. Indoor navigation patterns should be circular, but it should also be possible to have a hierarchical pattern on some days by minimal addition or removal of adjustable partitions or movable walls.

The centrality of these perceptual modalities is hardly surprising given the fact that people primarily experience the environmental space that they are embedded in by a combination of visual and locomotive exploration. Consequently, designers are inclined to project the effects of their design decisions using visuo-locomotive modalities as the principal driving force.

[1] Digital tools and virtual reality based studios have become rather regular in contemporary training methods in architecture design. Goldschmidt refers to this culture where an active engagement with the pencil is being slowly taken-over by digital modelling tools as the era of the '*dead pencil*' [15]. In our human-centred studies, spatial cognition and the visuo-spatial modalities of design analyses themselves are of principal relevance. The interface, e.g., digital vs. physical, by which the analytical modalities are applied is another issue altogether.



(a) Museum: Continuty as mutual visibility of locations (b) University: Visibility of landmarks for orientation (c) Circular Organization (d) Hierarchical Organization

Fig. 1. Spatial Design Scenarios with Built-Up Space

This is also reflected very well within academia, where research on human spatial cognition and computation for spatial and architectural design has identified topics such as visibility analysis, wayfinding and navigation, spatial reasoning, indoor spatial awareness etc. as core research strands [3]. Within the theory of architecture design, e.g., as approached within a conventional architecture design education, notions of *Form, Space, and Order* [8], and their implications and ramifications from a visuo-locomotive viewpoint are mainstream. Pragmatically, the centrality of visual and motion based analyses is also most directly evident in early design sketches and plans of architects.

We propose that the foundational informatics of design systems, tools, and analytical aids concerned with creative spatial design and engineering tasks should therefore be based on modalities of human spatial cognition at the scale of everyday human perception and thinking. We propose that design semantics, commonsense spatial cognition, and visuo-spatial abstraction and computing should be the driving forces underlying the foundations of next-generation design computing systems and paradigms. The paper is written from the perspective of *spatial informatics* and addresses space at the scale of everyday human perception and thinking in the context of *spatial cognition*. We address 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 spatial computing for design in particular [2].

The paper is organized as follows: Section II presents the overall context of our research, its underlying motivations rooted in *design philosophy 101*, and an abstract overview of core concepts that are illustrated in the rest of the paper. Section III presents the visuo-spatial ontological constructs that constitute the cognitively-driven foundational elements of our proposed human-centred design computing framework. These elements directly relate to the human spatial cognition modalities involving the visuo-locomotive exploration of space. Section IV presents an exemplar: a declarative programming framework that demonstrates the manner in which the primitive human-centred constructs of Section III may be operationalised toward functional design representation and reasoning within next-generation design computing systems. We conclude in Section V.

II. Functional Spatial Design

From a human-centred viewpoint, we discuss the centrality of form and function in spatial design, and the inherent inability of contemporary design systems to innately support these notions from a design modelling and computing viewpoint.

A. Spatial Design as 'Structuring Empty Space'

"*Form follows Function*" [25] and "*Ornament is Crime*" [19]—these two doctrines have been the cornerstones of the Modernist tradition in engineering design. Within the domain of architectural design, the broad interpretation that these doctrines lead to is that the *structural form*, i.e., *shape*, *layout*, *connectivity*, of a spatial design (e.g., for built-up space) should be primarily determined by its practical *function* or *purpose*. Much of the literature in the philosophy of design and architecture, and the ensuing debates thereof, have focused on the semantics of *functions* with respect to design artefacts and the causal link between *form* and *function*. Special emphasis has also been on the question of whether or not form should, or indeed does, wholly or in part follow function.

Spatial design for architecture is about '*space*': empty space, spatial structures, and the process of structuring. Architects organize empty space by building-up structures and artefacts of our everyday existence and structuring transforms and organizes empty space into something of a desired *form*, *function*, and *semantic connotation*. This structuring of empty space may be perceived as a process of creative, aesthetic, and functional problem solving; it is this structuring, and problem-solving that is the principal concern of this paper. Our operational understanding of structure and function relates to an '*iterative refinement by automated design assistance*' workflow [21], and is identifiable with respect to the *modelling–evaluation–re-design* phases in design assistance, for instance, as interpreted within the ontological framework of the Function-Behaviour-Structure (FBS) model [14], [26], [27] of the design process. The basic understanding is that a designer or an architect envisions a structure with respect to its anticipated behaviours that would satisfy desired functions.

B. Ching's Form, Space, and Order

Francis Ching, in his widely adopted morphological study of problem-solving in (architecture) design, presents a discourse on the core architectural elements of *form, space, and order* [8]. Ching illustrates the complex interrelations between fundamental design elements, patterns, and constructs occurring within systems of *space organization, physical structure, and enclosure* as they accrue in the design and organization of the built environment. Ching's work, which is definitorial and constitutes a basic part of any curriculum in architecture design, has a clear emphasis on notions of *structure, function, and purpose*. To quote Ching:

"Fundamentally, the physical manifestations of architecture accommodate human activity. However, the arrangement of the elements of form and space will determine how architecture might promote endeavours, elicit responses, and communicate meaning. These elements of form and space are presented, therefore, not as ends in themselves, but as means to solve a problem in response to conditions of function, purpose, and context - that is, architecturally."

The main message behind invoking this line of thought is to emphasise the fact that notions of design semantics, structure, and function are mainstream within the philosophy of architecture design. Furthermore, these, being an essential constituent of an architect's training, are also explicitly known and understood by designers. Yet, contemporary architectural design with its computer-aided methods, tools, and paradigms regards the eventual products of design activities as isolated "*frozen moments of perfection*".[2] Human-centred modalities of perception, action, experience, conception, and design semantics do not explicitly constitute the core building-blocks of contemporary CAAD systems. Specifically, even within state-of-the-art design tools, notions of semantics, structure, function, behaviour and user-centred design are not accessible to the designer. For instance, given the design tasks and requirements, exemplified in (S1–S3), concerning spatial cognition centred analysis of designs, a designer or architect would be left to ones own creative and analytical faculties, and potentially access to highly specialized custom analytical tools, during the iterative refinement process. Aspects such as modelling of form and function, simulation of people dynamics, visibility, way-finding, and circulation analyses are not commonplace within design systems. The paradigmatic foundations of computer aided architecture design still rests on points, line-segments and polygons. Contemporary CAAD systems simply lack notions of design semantics, and they do not provide the inherent capability for designers to explicitly apply their learned human-centred notions of design semantics during the professional design process.

C. Structure, Function, Malfunction

For the purposes of this paper, we interpret *structural form* and *artefactual function* as elaborated on in the following:

C1. *Structural Form.* The *structural form* of an environment is an abstraction mechanism generally corresponding to the layout, shape, relative arrangement and composition at the common-sense level of spatial entities, artefacts and other abstract or real elements that are modelled geometrically, interpreted or derived within a design system. The only conceivable premise underlying this notion is that it should be possible to communicate the conception of the structural form using one or more spatio-linguistic modalities – e.g., spatial prepositions, path and pattern descriptions, region and point-based abstractions – that may be wholly or partially grounded in an underlying physical structure either in metric space or in an abstract qualitative space.

C2. *Artefactual Function.* Artefactual functions (also referred to as '*functions*') and malfunctions correspond to a behaviour or set of behaviours that a particular structural configuration or arrangement produces or leads to. For the purposes of this paper, functions essentially correspond to behaviours associated with high-level design requirements that are ontologically interpreted as sets of constraints within a task-specific *design requirement ontology*.[3] This interpretation of functions only refers to those aspects that emanate directly from structural form; specifically, this paper is concerned with functions that are identifiable directly via semantic, physical, and logical constraints. Functions encompassing social, cultural, and economic constraints are not considered in this article.

This abstractly presented interpretation of *structural form* and the resulting *artefactual function* is applicable beyond the domain of architecture design, to a broad class of systems referred to as *spatial assistance systems* [6]. However, architecture remains the focus area in this paper.[4] Structural forms may also entail functionalities that may be interpreted in the context of design aesthetics, subjective emotional reactions, etc., as applicable within domains such as creative assistance in digital media design, and design of ambient or smart environments.[5] A discussion of these abstractions also inevitably requires a discussion of the underlying engineering aspects related to CAAD models: the notion of *structural form* is formally specifiable via a detailed characterisation involving graph-theoretic and qualitative, relational-algebraic formalisations. An in-depth technical overview of a multi-modal characterisation of the *structural form* of (indoor) spatial environments in the context of spatial design systems and industry standards is available in [5], [22], [23]. These details, excluded herein, are of orthogonal interest for this paper. Here, the aforestated abstract interpretation of structural form and artefactual function suffices.

III. A Visuo-Spatial Ontology for Functional Spatial Design

We present the visuo-spatial ontological constructs that constitute the cognitively-driven foundational elements of our proposed human-centred design computing framework. These elements directly relate to the human spatial cognition modalities involving the visuo-locomotive exploration of space. These primitives provide the semantic foundations, and the basic computational building blocks for high-level design languages, programming frameworks, or interactive design development environments.

A. Primitives: Artefacts and Affordances

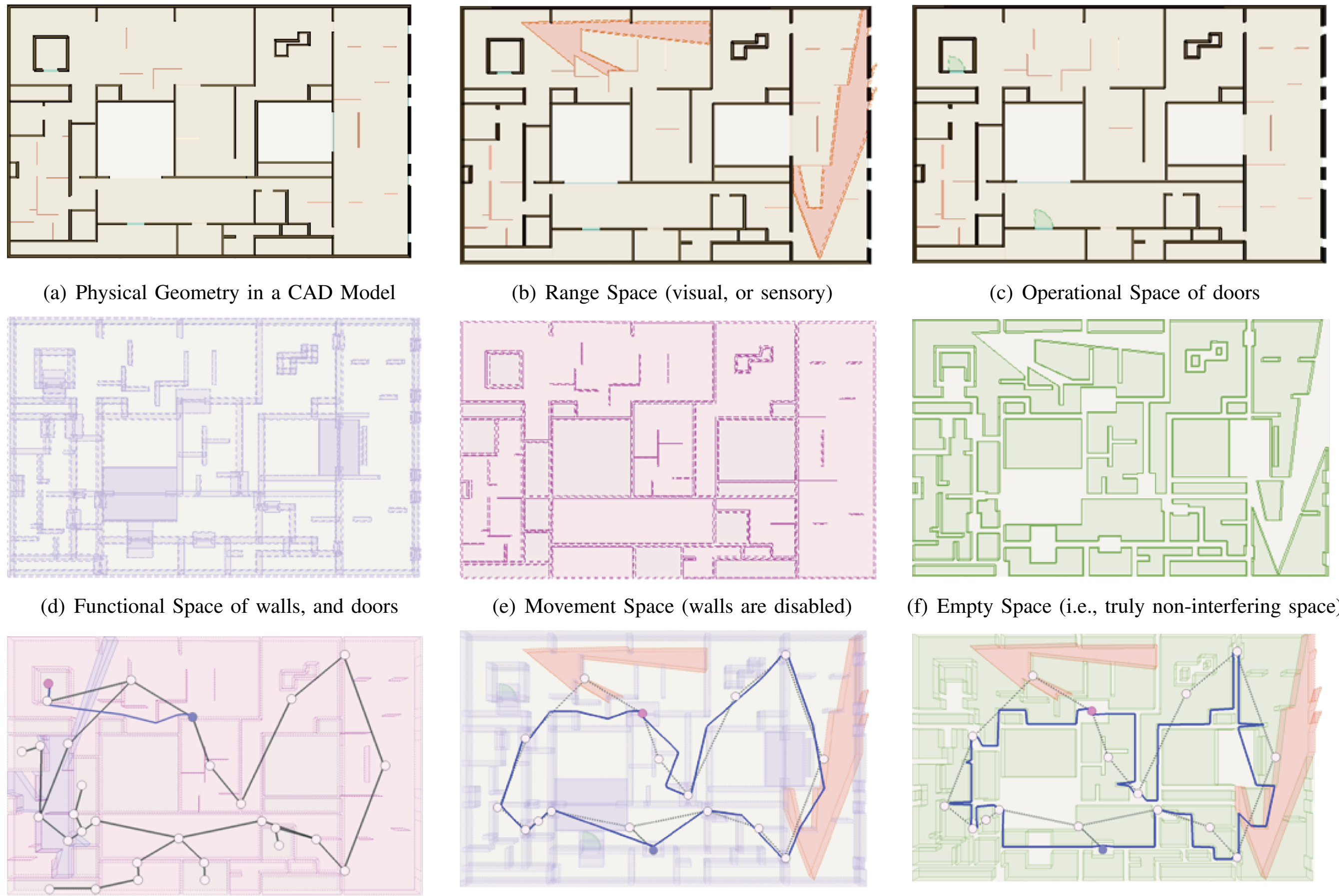
Semantic descriptions of designs and their requirements acquire real significance when the spatial and functional constraints can be expressed among not only strictly physical entities, but also for abstract *artefacts* and *afforandances* in the environment. For instance, consider a *spatial artefact* such as the *range space* of a sensory device (e.g., camera, motion sensor, view-point of an agent). This range space is not strictly a spatial entity in the form of having a material existence, but needs to be treated as such nevertheless. In general, design systems only contain purely physical entities. Therefore, it becomes impossible for a designer to model (e.g.,

[2]This is an expression that occurs in a related context in the book 'Eating Architecture' (Pg. 12), ed. Jamie Horwitz, Paulette Singley, MIT Press (2004).

[3]From the viewpoint of formally modelling an ontological terminology, these may also be interpreted as categories with specific relationships and properties specified in an architectural requirement ontology [4].

[4]In [6], a definitive take on the *conceptual, formal*, and *computational* aspects of '*space*' within spatial assistance systems has been included.

[5]Examples of media design assistance include tasks such as automatic story-boarding for film and comic design, virtual cinematography for film and animation; the relationship of this class of creative design work is available in [1], [6].



(a) Physical Geometry in a CAD Model
(b) Range Space (visual, or sensory)
(c) Operational Space of doors
(d) Functional Space of walls, and doors
(e) Movement Space (walls are disabled)
(f) Empty Space (i.e., truly non-interfering space)
(g) Route Graph (logical connectedness)
(h) Route Path (with actual path geometry)
(i) Affordance Path (i.e., with special properties)

Fig. 2. The Ontology of Artefacts and Affordances. Museum Calouste Gulbenkian. (System DSim).

visually) constraints involving spatial artefacts and affordances during the master planning phase. For instance, consider the following constraint: 'the motion-sensor should be placed such that the door connecting room A and room B is always within the sensor's range space'. In general, given a physical geometry (Fig. 2(a)), the following primitives may be identified:

A1. *Range Space*: This denotes the region of space that lies within the scope of a sensory device such as a motion or temperature sensor, or any other entity capable of visual perception. Range space may be further classified into other categories, such as *observational or visibility space*. The visibility space is a region of space from which an object is visible, i.e. an inversion of the commonly known notion of an *isovist*.[6]

A2. *Operational Space*: This denotes the region of space that an object requires to perform its intrinsic function that characterizes its utility or purpose, e.g., Fig. 2(c) illustrates the operational space of Doors.

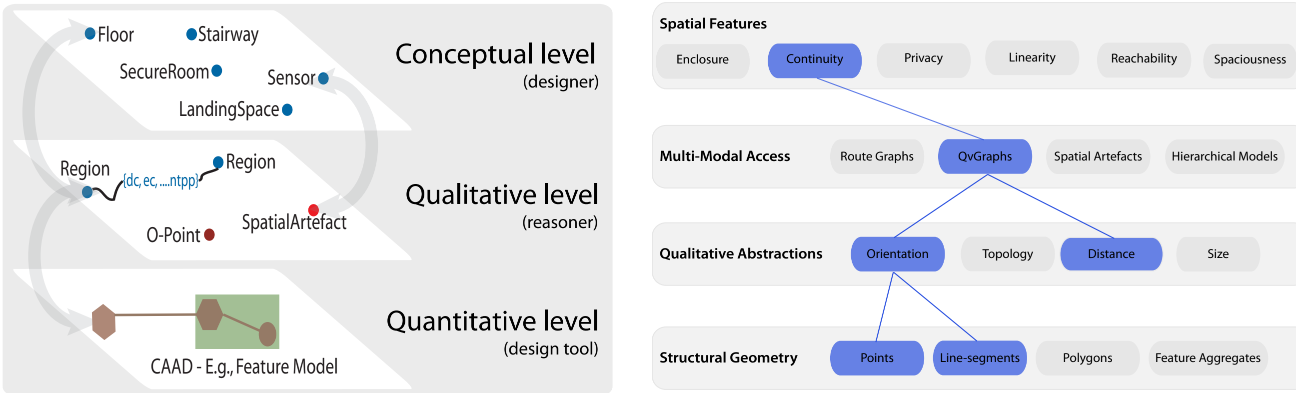
A3. *Functional Space*: This denotes the region of space within which an agent must be located to manipulate or physically interact with a given object, e.g., Fig. 2(d) illustrates the functional space for all physical entities in the design.

A4. *Movement Space*: These are topologically distinct locations bounded by place-delimiting objects (e.g. obstacles such as walls). Different conditions that define whether an object is an *obstacle* give rise to alternative movement spaces. (Fig. 2(e))

A5. *Empty Space*: In general, we define empty space as the truly non-interfering region of space within which humans can freely operate in the built environment. Non-interference is interpreted as absence of interaction with the physical space and spatial artefacts such as functional, operational, range spaces in the environment. (Fig. 2(f))

A6. *Topological Route Graphs and Geometric Route Paths*: Movement spaces are connected by place-transitioning objects (such as openings and doorways) to derive route graphs. Topological paths are sequences of movement spaces (or "places") and transitioning objects through the route graph. In contrast, geometric route paths are bounded curves embedded in the environment along which an agent can move without colliding with obstacle objects. In essence, the movement space provides the set of all topologically equivalent (actual) geometric routes between two locations. Using the construct of movement spaces, we can study *sets* of geometric routes,

[6] In order to calculate the visibility space we extend the notion of isovist from being the set of points visible from a given *point*, to the set of points visible from a given *line segment*, which is then generalised to a polyline, thus corresponding to the bounding curve of the object in question.



(a) Multi-Perspective Modules

(b) Multi-Modal Characterization of Spatial Features

Fig. 3. Multi-Perspective Semantics (for representation, and reasoning)

and ask questions about whether geometric routes exist that have certain properties, or whether all geometric routes fulfil a given property. (Fig. 2(g))

A7. *Affordance based Route Paths*: By providing alternative definitions for place-delimiting and place-transitioning objects, we can derive agent-specific route graphs. For example, consider firefighters navigating through a burning builiding in search of victims. The smoke drastically reduces occupant visibility and therefore the firefighters' sense of orientation depends heavily on reference features such doors, walls, corners, and large pieces of furniture [18]. Thus, the standard geometric paths (e.g., Fig. 2(h)) are not suitable for analytical purposes. A more effective, domain-specific geometric path is defined by the arrangement of salient features such as doors and windows along room walls, as illustrated in Figure 2(i). This is derived by specifying the condition that *movement space* must be within the *functional space* of a wall.

A8. *Qualitatively Annotated Visibility Graphs* (QvGraphs): These are an extension to the concept of a *Visibility Graph* [20], [10]. In computational geometry, a visibility graph of a polygonal scene shows the intervisibility relations between a set of points (indicating locations, obstacles, and so on) in a scene, as geometrically constituted within the Euclidean plane. Specifically, visibility graph vertices correspond to point locations and edges represent a visible connection between them. QvGraphs extend visibility graphs by deriving and annotating the *visibility link* with (potentially disjunctive) knowledge about spatial relationships pertaining to one or more spatial domains such as topology, orientation, and distance. Fig. 1(a) illustrates an example of a visibility graph of a museum lobby. The direction of the edges indicates the direction of the binary qualitative relations; for example, the ReceptionDesk is right_of the LobbyEntrance, indicated by the direction of the edge in the QvGraph, although the visible relation in this example is symmetric.

B. Multi-Perspective Modelling with Primitives

Consider the illustration in Fig. 3(a): an abstraction such as a Room or Sensor 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 these types are transferred to 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. Such primitive concepts are necessary yet in conflict with the mental image and qualitative conceptualisation of the designer. 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.

Multi-Perspective Characterization of 'Continuity'. Continuity, as a (perceptual) spatial feature, amongst a set of entities or locations may be, for instance, identified as mutual visibility among the entities and locations under consideration. In addition to mutual-visibility as an interpretation of continuity, one may expect additional constraints involving relative and absolute positional constraints among the entities (Fig. 3(b)). Additionally, one may further refine the notion by the inclusion of distance constraints, e.g., "*X should not only be visible from Y, it should also not be too far away...*". At a lower-level of abstraction, the notion of continuity therefore translates to a set of visibility, orientational and distance constraints over a spatial structure, which is precisely the perspective offered by the modality of a QvGraph (Section III; A8).

Figure 3 illustrates the overall intuition underlying our interpretation of multi-perspective semantics. Indeed, this is a formally specifiable notion: [4] includes a detailed specification of the manner in which this may be formalised with a formal *description logic* with the aid of the semantic modelling language OWL – Web Ontology Language (OWL).

C. Class Diagram of Artefactual Spaces

The classes of our visuo-spatial language can be divided into levels as illustrated in the class diagram in Figure 4. The geometric level represents objects using points, lines, polygons and so on, along with basic topological relationships (such as the edges between 3D points that define a geometric face). The architecture, engineering and construction (AEC) level defines key concepts and relationships in the design domain such as walls, openings, doors, building storeys, and spaces. The human-centred level extends the AEC level with spatial artefacts, networks of high-level relationships between products derived from the spatial artefact regions, and the topological and geometric routes through the environment. The regions associated with spatial artefacts are grounded in the geometric level, and thus the high-level human-centred relationships between products are derived from both the semantics of products and their geometric physical spaces. Spatial descriptors formalise intuitive, domain-specific spatial concepts[7] with first-order rules that refer to qualitative spatial relations (in the relational-algebraic sense) [9] according to the context and the semantics of the objects involved.

Each floor is represented as a two dimensional floor plan by projecting objects and artefactual spaces onto a plane parallel to the ground. Height and elevation information of the bounding cuboid is maintained so that some vertical ordering of objects is preserved (e.g. we know if a pot plant is sitting on top of a bookshelf or inside the bookshelf).

A product is *connected* to another product's spatial artefact when its physical space intersects with the artefact's spatial region (*RelSpatialArtefactConnects*).[8] Networks of these connection relationships form traversable graphs. For example, a route graph consists of a network of movement spaces and doorways; a QvGraph graph consists of a network of visibility spaces and products annotated with qualitative spatial relations. Taken together, these form a route-visibility network that can be used to easily identify certain products that are visible along a given route.

IV. A Declarative Programming Model for Functional Design Computing

We present a high-level, declarative programming model that utilises the primitive human-centred ontological constructs of Section III. This model should be interpreted as the foundational computational machinery that high-level visual or graphical languages, specifications frameworks, and interactive design development environments may utilise. In essence, we seek to demonstrate one working model for next-generation human-centred computer aided spatial design. Our model is rooted in the declarative semantics of *constraint logic programming* [16]; however, other models such as functional languages, diagrammatic representations, or even conventional production scale object-oriented settings are also possible.[9] If necessary, the semantics of the rule-based specification of logic-programming used in this section have been briefly outlined in the Appendix.

A. Identifying Qualitative Changes in an Environment

Minor changes in a design can dramatically influence the occupants' perception and behaviours within a space under certain conditions, such as blocking paths and causing congestion, despite there being no significant change in the overall topology of the room's *movement space*. Consider Figure

[7]Fig. 4 only illustrates a small exemplary sample such as *left_of* and *across_from*.

[8]The geometric interpretation of *intersects* is customised according to the semantics of the objects.

[9]The theoretical foundations of our proposed constraint logic programming based computational framework are available in [5]. A good primer on logic programming using the PROLOG language is [7]. Here, it suffices to understand that the symbolic, logic-based knowledge representation and reasoning engine of a particular form of the PROLOG language with support of polynomial equations provides the necessary design computing capability for deriving the primitive visuo-spatial elements of Section 3 (A1–A8).

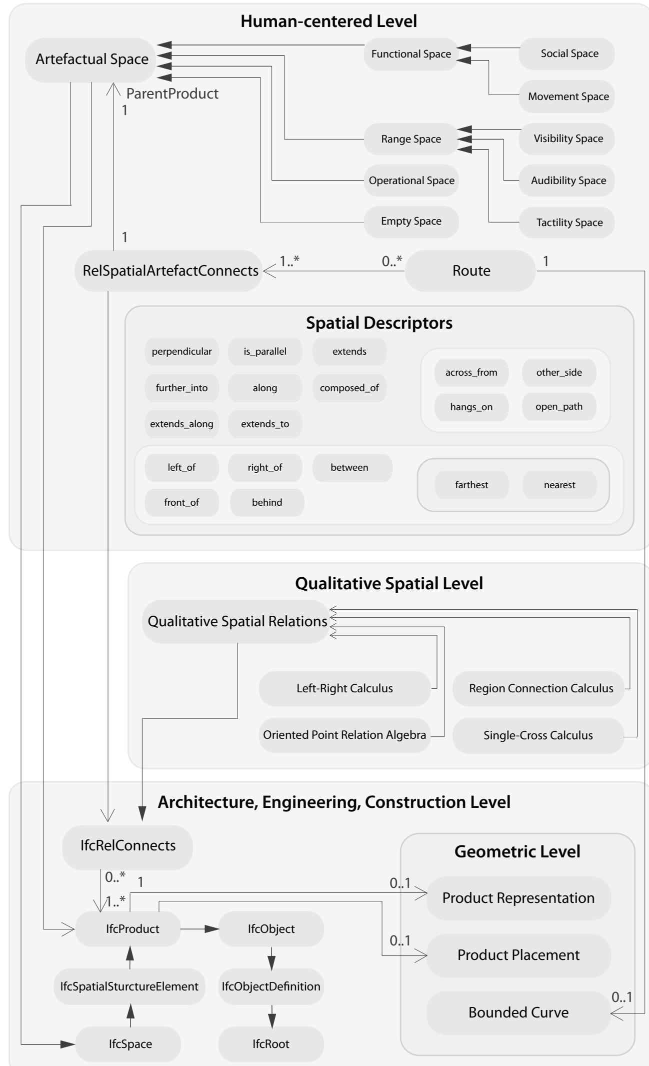


Fig. 4. UML class diagram of the human-centred spatial artefact and route classes in the context of (extracts of) the Industry Foundation Classes (IFC) [13] design-level and geometric-level classes.

5: island displays and perimeter displays have been shown to reflect different circulation patterns of visitors through museum gallery rooms [24]. Here, the second and third gallery arrangements are topologically equivalent from the perspective of *empty space*, despite having geometrically rather distinct configurations, as they both consist of one empty space region without holes. Thus, the first arrangement is qualitatively distinct from the others as the empty space region now contains a hole. In contrast, the first and second gallery arrangements are topologically equivalent from the perspective of movement space, as they both consist of one space with six holes.

```
similar(RoomA,RoomB) :-
    empty_space(RoomA,_,APolygons),
    empty_space(RoomB,_,BPolygons),
    topology(APolygons,BPolygons,isomorphic).
```

B. Perceptual Continuity in Space

Previously, we introduced *continuity* as a general pattern

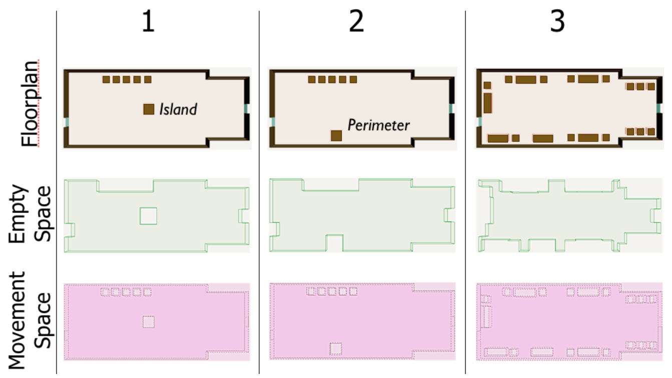


Fig. 5. Topological properties of empty spaces highlight some key similarities and differences between spatial configurations.

denoting mutual visibility and reachability amongst a set of locations.

▷ Local continuity between a set of objects (e.g., in a room) is evoked when people (e.g., visitors in a museum) that are engaged with any object from the set have a visual connection with the other remaining objects in the set. To be *engaged* with an object means simply to be located within the functional space of that object, and *visual connection* is determined using visibility relationships available in the QvGraph. Local continuity between n objects can be checked by the presence of a complete n-clique in the available QvGraph. Figure 1(a) illustrates the QvGraph used to determine regions of continuity in the lobby of the museum reception of Fig. 1(c).

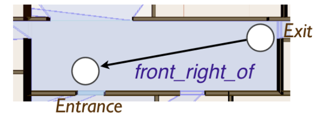
```
localContinuity(MoveSpace, Objs) :-
      movement_space(_,MoveSpace,MPolygon),
      physical_space(_,Objs,OPolygons),
      topology(MPolygon,OPolygons,contains).
      qvGraph(Objs,Objs,visible).
```

▷ A sense of global continuity and orientation through an environment is maintained if, as visitors moves through the environment (e.g., museum), they have visual contact with either the entrance or the exit point of the current location, or orienting features such as signage or landmarks (e.g., in an airport). As illustrated in Fig. 6, a sense of continuity is possible if *some* geometric route path has this property; continuity is guaranteed if *all* geometric route paths have this property. We can determine whether *all* geometric paths that follow a given topological path allow a visitor to maintain visual contact with orienting objects by checking whether the visibility spaces of the objects *contain* the movement spaces. This would mean, for instance, that visitors can see some signage from any location that they happen to be standing at along a topological route graph.

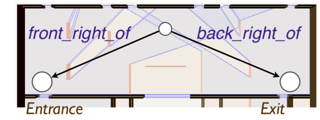
```
continuity(MoveSpace,Doorways) :-
      movement_space(_,MoveSpace,MPolygons),
      visibility_space(Doorways,_,VPolygons),
      topology(MPolygon,VPolygon,inside).
```

C. Visibility and Navigation

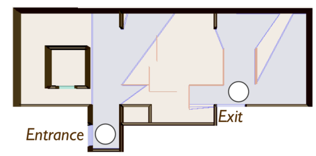
Visibility analyses may be extended to outdoor scenarios too, such as the university campus design task described in Section 1 (requirement S2). As people move through the various locations of the campus, a prominent Tower provides a sense



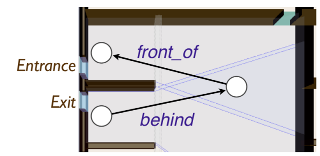
(a) All paths through this room are guaranteed to maintain a sense of continuity.



(b) The paths through this room that lie within the visibility spaces and their intersections maintain a sense of continuity.



(c) Regardless of the path taken through this room, the occupant will lose visual contact with the orienting doorways and thus may lose their sense of continuity.



(d) The relative orientation of the doorways requires the occupant to turn around before making visual contact with the next orienting way point.

Fig. 6. Continuity as the occupant moves between spaces in a building.

of orientation. This requirement may translate to the following rule:

```
notVisibleFromTopologicalPath(Objs,Route,At) :-
      topological_path(Route,Path),
      movement_spaces(Path,M,MPolygon),
      visibility_spaces(Objs,_,VPolygon),
      not(topology(MPolygon,VPolygon,overlaps)).
```

D. Circulation Pattern Analysis

Figure 1(c) illustrates a circular flow through the gallery. By simulating the removal of one central partition or wall, the designer is able to radically alter the circulation pattern into a more hierarchical (hub-based) layout, as illustrated in Fig. 1(d).

E. Spatial Feature Analysis

▷ Local Linearity. A room 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, and fewer holes themselves containing nested regions (assuming that the rooms have the same number of entry and exit points).

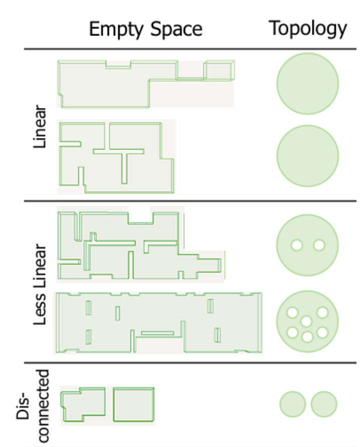


Fig. 7. Empty space topology indicates the linearity of a space.

▷ Spaciousness. An environment with a sense of openness and volume can have many objects around the perimeter of the room, but critically must have no large objects, or very few, in the central region of the room. Centrally located objects can occlude mutual visibility of large portions of a room, and objects positioned on walking paths, breaking linearity, can create a sense of clutter [17], [12], [11]. Thus, spaciousness may be evaluated using QvGraphs and empty space topology.

```
spacious(Room) :-
      get_contained_objects(Room,Objs),
      qvGraph(Objs,Objs,visible),
      linear(Room).
```

V. Conclusion and Outlook

Contemporary architecture design software tools, systems, and processes regard eventual design products as isolated "*frozen moments of perfection*". Even within state-of-the-art design tools, aspects such as commonsense, semantics, structure, function, behaviour, people-centred design - concepts that are implicitly known to designers - are yet to come to the fore. As a broad research goal, and by the concrete contributions of this paper, we position human-centred, cognitively-driven design computing as an area of paradigmatic significance. An operational goal of our research is to develop design tools, systems, and frameworks that assist designers at all stages of a functional design process. Directly using the computational design analysis methodologies developed in our research project DesignSpace, we have attempted to: (a) provide a high-level overview of the paradigm of functional spatial design, (b) illustrate an application-guided practical framework that operationalises the core concepts of functional design, and (c) position human-centred, cognitively-driven spatial design computing as an area of significant social and industrial impact.

The ontological characterisations in our framework / system are indeed not comprehensive. We selectively build on those elements that we consider to be most necessary for the range of visuo-locomotive analyses that we are interested in (e.g., circulation, visibility), and that too for a select range of functional design tasks involving public spaces (hospitals, airport, museums). Extending the scope of our human-centred ontology is a topic of ongoing research. We are also focussing on the early conceptual design phase in architecture. Here, we are developing a notational scheme for the externalisation of architect's early plans via a diagrammatic representation. For instance, a combination of modalities such as bubble diagrams and visitor sequence diagrams are being developed. The focus is on functional design tasks involving Hospitals, Museums, and other built-up public spaces.

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