Analytical Computing for Spatial Design:
An Artificial Intelligence Perspective

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Abstract

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:

   – Contemporary CAAD tools provide robust geometric modeling methods; how can the future evolution of design computing bring notions of design semantics, structure, function, and people-centred design to the fore at an ontological, representational and computational level?

   – What is the role of specialized forms of visuo-spatial perception, abstraction, and common-sense spatial reasoning, within the broader realm of design computing, spatial design assistance, and tools for design learning and education?

   – What is the nature and form of the assistive design 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 interaction design aspects of spatial design (assistance) systems?

This article presents an overview of the above stated aspects in the backdrop of relevant examples; we present abstraction, representation, and reasoning problems involving the formal modelling of *structural form* with respect to a desired / anticipated *artefactual (mal)function*. The discussion is grounded in the domain of assistive decision-support for computer-aided architecture design. Our methods are essentially AI-centric, i.e., we relate most directly with the articulation of the *Science of Design* by Herbert Simon and the paradigmatic relevance of Artificial Intelligence in that context.

Keywords: *spatial cognition; spatial representation and reasoning; knowledge engineering for design; design computing and cognition; computer-aided architecture design.*

1. Artificial Intelligence and Design Computing

The significance and the paradigmatic relevance of Artificial Intelligence in Modern Design is intertwined with Herbert Simon's original articulation of the *Science of Design* (Simon, 1969; Simon, 1996), 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.[1] From a topical viewpoint, the knowledge representation and reasoning area within artificial intelligence has been the cornerstone of most formal AI inroads in so far as *problem-solving for design* is concerned. In the last two decades, 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 conceptualization, functionality specification, geometric modelling, structural consistency & code-checking, optimization, collaborative (design) workflow management, design creativity, and a plethora of other issues.[2]

Our semantic and visuo-spatial abstraction and computational methods are situated within this AI-centric view of the science of design; influenced by the need to abstract, formally define, model, and reason about structural form & artefactual (mal)function, our interpretation of analytical design computing encompasses aspects we regard as crucial (Bhatt, Schultz, & Freksa, 2012):

- semantic modelling, spatial abstraction, & multi-perspective representation
- design analysis by inference patterns supporting diagnostic & hypothetical reasoning
- assistive feedback / communication with designers

The aspects deemed essential correspond to problems that accrue within a 'iterative refinement by automated design assistance' workflow, and are identifiable with respect to the *modelling–evaluation–re-design* phases in intelligent design assistance, for instance, as interpreted within the ontological framework of the Function-Behaviour-Structure (FBS) (Gero, 1990; Gero, Tham, & Lee, 1991) model of the design process. With respect to the iterative refinement work-flow, the basic research questions within the context of AI-based assistive design computing include:

1. Semantics: formal modelling of design requirements, and the role of knowledge engineering in that regard
2. Spatial abstraction: abstraction of CAAD-based geometric information into the qualitative domain via the use of formal spatial representation and reasoning techniques
3. Spatial reasoning: the application of spatial reasoning, and its interaction with other forms of reasoning (e.g., conceptual), as a basis for checking for design requirement consistency

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1. Henceforth, by design we refer to spatial design in general, and in specific to architectural design, which we regard to be an instance of spatial design. By conventional design systems, we refer to computer-aided architectural design (CAAD) tools.

2. 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). The collected works of (Gero, 1990; Gero, Tham, & Lee, 1991; Krishnamurti, 2006; Chandrasekaran, 1990; Brown, 1993; Akin, 1993; Hirtz et al., 2002) are a rich source of reference and contextualisation.

4. Hypothetical reasoning: the role of hypothetical reasoning (e.g., by abduction) as a means to support a diagnostic and recommendation function
5. Assistive feedback: visual and diagrammatic modalities as a means to interact & communicate assistive feedback with the designer

The above problem aspects have partial overlaps and many interrelationships. However, the paper attempts to characterize these independently with running examples. The paper is organized as follows:

Section 2 provides an overview of the iterative refinement cycle in design. Section 3 presents a broad overview of assistance-driven anaytical design computing for architecture; key representational and computational modalities are discussed, and we also attempt to ground the discussion in Sections 2 and 3 with examples that further illustrate the agenda of our research, and the range problems addressed. We summarize in Section 4, and at the same time, also reflect upon some of the issues raised by Gero (1991) in his statement of "*Ten Problems for AI in Design*".

2. Iterative Refinement in Spatial Design

Spatial design as a problem-solving activity typically consists of the Conception – Modelling – Evaluation – Re-modelling cycle. Essentially, a designer in this case is considered to be an *agent of change*, who in the absence of any computational assistance, may be intuitively regarded as traversing a complex configuration space of possibilities, and selecting one course of action (guided by domain knowledge, expertise, cognitive capabilities, specialized requirements, aesthetic preferences and so forth) that produces a desired product / design.

A Design Task. As a basic use-case, consider an architect / engineer specialising in the design and development of building automation systems and smart environments. A typical design challenge would be:

> Design the layout of an office environment to satisfy structural and functional requirements that collectively aid and complement (and never hinder) the building's automation systems (monitoring devices, sensors, etc.), and which, by implication, facilitate the intended smartness of such automation systems.

From the viewpoint of the overall design requirements, aspects of this problem explicitly pertain to the functionality (e.g., security, privacy, building-automation, accessibility) of the space being modelled, structural code-checking with respect to building regulations, and also possibly specialized client demands. Some example requirements follow: **(R1)**. certain areas within a building / floor / room should (not) be trackable by sensing devices such as cameras, motion-sensors, **(R2)**. regional statutory requirements that stipulate structural constraints and other categorical specifications, e.g., disability access codes, design guides, **(R3)**. client specification: as much as possible, the operation of doors should be non-interfering with the functionality of nearby utilities / artefacts.

Figure 1 is a schematization of the consistent and inconsistent models of the example requirements / scenarios in (**R1–R3**). The following aspects, marked as [1–4] in Figures 1(a)–1(b), make the plans of Figure 1 (in)consistent with respect to (**R1–R3**):
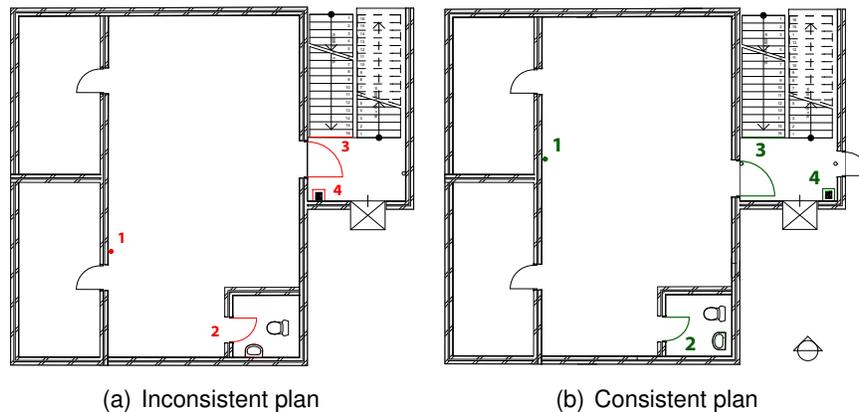
(a) Inconsistent plan (b) Consistent plan

Figure 1. Design Requirements: Example Spatial Interpretations (explanations given in the text).

- the sensor / camera is placed at a place where a private area such as the wash-room is within its range (No. 1)
- the operating space of the door of the wash-room interferes with the functional area of the wash-sink, and this arrangement is also not conducive, given disability access requirements (No. 2)
- the operation of the main entrance door interferes with the function of the telephone next to it, and from a structural viewpoint, is also not an ideal placement given its proximity to the staircase (No. 3, 4)

From a design computing viewpoint, one may imagine the search space to consist of spatial configurations –topological, orientational arrangements– and the spatial transformations that are possible, e.g., with respect to a movement taxonomy, as the available actions that produce a re-arrangement. The objective of iterative refinement in general, be it automated or human, is to create consistent models that fulfill the requirements as they are conceived at design time. Albeit a bit limiting, for this particular case, the automation necessary to realize the re-configuration may be identified as a limited form of assistive spatial design intelligence that guides the designer toward a solution that meets the pre-specified requirements, such as those stipulated in (**R1**–**R3**).

Automated Design Refinement. The following aspects of iterative refinement (**I1**–**I3**) are deemed crucial: (**I1**). *Modelling – Design Abstraction*: this aspect encompasses issues ranging from semantic specifications, taxonomic representations, qualitative abstractions of geometric models, and modularity of information representation, (**I2**). *Convergence – Reasoning*: this aspect constitutes the various *modes of inference* that constitute the computational manifestations of the assistive design support, (**I3**). *Assistive Feedback – Visualization*: this aspect constitutes mechanisms and modalities to provide diagnostic feedback and other forms of support within a conventional CAAD workflow

Indeed, the possibilities to broaden the interpretation of this manner of intelligent assistance are rather extensive, ranging within a wide array of techniques from the computing, cognitive, psychological, and aesthetic disciplines. Our preliminary focus in assistive design computing has centred

on spatial cognition, and is guided by the aim to formally and computationally understand the relationship between the "structural form" and "artefactual function" within the domain of spatial design. Further elaborations are presented in Section 3.

3. Analytical Design Computation for CAAD Systems

Contemporary Computer-Aided Architecture Design (CAAD) systems, at their core from a modelling and information-theoretic viewpoint, consist 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.

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 be based on modalities of visual and spatial cognition at the scale of everyday human perception and thinking. 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 paradigm. In particular, some of the aspects that we consider to be the core *people-centred modalities* within the purview of analytical design computing are (Bhatt, Schultz, & Huang, 2012):

1. Visuo-locomotive primitives
2. Spatial perception and awareness
3. Action and dynamics
4. Environmental affordances and experience
5. Design conception and semantics

We approach the problem of architecture design from the perspective of *spatial informatics*, and address *space* at the scale of everyday human perception and thinking in the context of *spatial cognition* (Bhatt, Schultz, & Freksa, 2012). 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 logic-based geometric and spatial representation and reasoning in particular (Bhatt et al., 2011).

The kinds of fundamental reasoning tasks that may be identified within the purview of assistance-driven analytical design computing spans a wide spectrum, e.g., including reasoning patterns such as spatial property projection, spatial simulation, spatial planning (e.g., for configuration problems), explanation with spatial information (i.e., causal explanation, hypothetical reasoning) to name a

few. Both within and beyond the range of domains identified here, these are inference problems that involve an inherent interaction between *space, actions, events, and spatial change* in the backdrop of domain-specific commonsense knowledge about the world (Bhatt, 2012). We now elaborate on some of the representational and computational aspects concerned with analytical design computing.

3.1 Modelling Form and Function

"*Form follows Function*" (Sullivan, 1896) and "*Ornament is Crime*" (Loos, 1930)—these two doctrines have been the cornerstones of the modernist tradition in engineering design.[3] Restricting the application of these doctrines to the domain of architectural design, the interpretation that it leads to is that the *structural form*, i.e., *shape*, *layout*, *connectivity*, of a building should be primarily (or more rigidly: *solely*) determined by its practical *function* or *purpose*. Much of the literature in the philosophy of design and architecture (Vermaas et al., 2008), 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*, stressing the question of whether or not form should, or indeed does, wholly or in part follow function[4].

Structural Form and Artefactual Function in Design Analysis: From the viewpoint of this paper, analytical design computing is primarily concerned with the issues surrounding the formal interpretation of the terms "structural form" and "artefactual function", in particular with respect to the interpretation of these concepts in the context of a CAAD-based workflow. This is crucial, since it is necessary to explicitly put these notions into practice by investigating what precisely does it mean to model *form* and *function* within an intelligent architectural design assistance system. We note some examples:

Example 1. Bremen (Germany) Building code (BremLBO, 2003)):

(a). *Staircase / Treppen* (§35 (10), pg. 24):

> "*Steps of a staircase may not be connected directly to a door that opens in the direction of the steps. There has to be a landing between the staircase steps and the door. The length of this landing has to have at least the size of the door width*".

Example 2. US Courts Design Guide 2007 (US GSA, 2007)

(b). *Barrier-Free Accessibility* (pg. 4-3):

> "*Courtroom areas used by the public must be accessible to people with disabilities. Private work areas, including the judge's bench and the courtroom deputy, law clerk, bailiff, and court reporter stations, must be adaptable to accessibility. While all judges benches and courtroom personnel stations do not need to be immediately accessible, disabled judges and court personnel must be accommodated*"

(c). *Psychology, Culture and Aesthetics* (pg. 3-1, 4-4):

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3. Whereas Louis Sullivan articulated the relationship between of 'Form and Function', the original attribution goes to the 18th century Italian architectural theorist Carlo Lodoli.
4. Dorst and Vermaas (2005) present a critical review of the Function-Behaviour-Structure model. The discussion sheds useful insights about the nature of form-function.

"The architecture of federal courthouses must promote respect for the tradition and purpose of the American judicial process. To this end, a courthouse facility must express solemnity, integrity, rigor, and fairness."

"All architectural elements must be proportional and arranged hierarchically to signify order-liness. The materials employed must be consistently applied, be natural and regional in origin, be durable, and invoke a sense of permanence."

"The height and location of the judges bench expresses the role of the judge and facilitates control of the court. Generally, the judges bench should be elevated three or four steps (21-24 inches or 525-600 mm) above the courtroom wall."

(d). *Visibility* (pg. 3-2, 16-9):

"The entrance or entrance vestibule should be clearly visible and recognizable as such from the exterior of the building. The vestibule should be a minimum of 7 feet in depth and able to handle the flow of traffic at peak times."

"A duress alarm must be easily accessible and visible to all occupants."

Example 3.   A Pattern Language (Alexander, Ishikawa, & Silverstein, 1977)

(e). *Sunny Counter* (pg. 916–918):

"Place the main part of the kitchen counter on the south and southeast side of the kitchen, with big windows around it, so that sun can flood in and fill the kitchen with yellow light both morning and afternoon"

At this stage, we leave the readers with their imagination as to the formal interpretation of the above examples – some have a clear and well-defined spatial structure within a design, whereas others are only indirectly specifiable. Design assistance tools and analytical design computing mechanisms should be concerned with the extent to which functional aspects such as those exemplified herein could be formally interpreted in strictly semantic and spatial terms (Bhatt, Hois, & Kutz, 2012); from a computational viewpoint, it is clear that adequate conceptual, spatio-linguistic and qualitative modelling techniques are necessary for representing and reasoning about *design artefacts* and *patterns* entailed by designer expertise (Bhatt, Schultz, & Freksa, 2012).

3.2 Design Artefacts: Conceptualization and Formal Representation

Design involves an interplay between the designers' conceptualization, the handicaps of the computational constructs of the design tool, and the limitations of the bridges that connect the conceptual with the computational. Professional design tools simply lack the ability to exploit the expertise that a designer is equipped with, but unable to communicate to the design tool explicitly in a manner consistent with its inherent human-centred conceptualization, i.e., *semantically* and *qualitatively*. Modelling in design has to be focussed on representation of *design semantics*, *artefactual modelling* capability, and support for *multi-perspective modularity*; these aspects are discussed below.

Design Semantics.   An expert's design conceptualization is semantic and qualitative in nature—it involves abstract categories such as Rooms, Doors, Sensors and the spatial (topological, directional, etc.) relationships among them, e.g., '*Room A and Room B have a Door in Between, which is monitored by Camera C*'. Whereas this example is rather specific, typical real-world constraints are
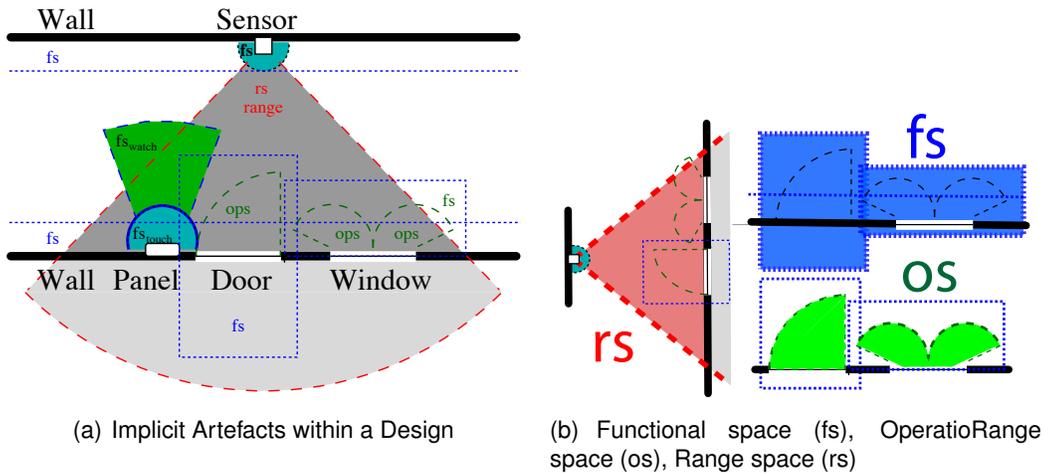
(a) Implicit Artefacts within a Design

(b) Functional space (fs), OperatioRange space (os), Range space (rs)

Figure 2. Spatial artefacts are entities, which unlike regular spatial objects, do not have a physical manifestation in reality (or within a design), but need to be treated as such for all practical / reasoning purposes. **Illustration adapted from** (Bhatt, Dylla, & Hois, 2009); see (Bhatt, Schultz, & Huang, 2012) for examples from a functional system.

mostly underspecified or fuzzy (e.g., see Section 3.1). Therefore, any vision of specialised analytical computing for design has to handle to the modelling of designer / design semantics in an explicit manner, e.g., using formal knowledge engineering constructs such as formal ontology modelling languages.

Spatial Artefacts. A crucial aspect that is missing in contemporary design tools is the support to explicitly characterize the artefactual aspects, and the functional requirements ensuing therefrom, within a design. Semantic descriptions of designs and their requirements acquire real significance when the spatial and functional constraints are among strictly spatial entities as well as abstract *spatial artefacts*. For instance, although it is possible to model the spatial layout of an environment at a fine-grained level, it is not possible to model *spatial artefacts* such as the *range space* of a sensory device (e.g., camera, motion sensor, view-point of an agent), which is not strictly a spatial entity in the form of having a material existence, but needs to be treated as such nevertheless. In general, architectural working designs only contain physical entities. Therefore, it becomes impossible for a designer to model constraints involving spatial artefacts at the design level. 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*'. Bhatt et al. (2009) identify three types of spatial artefacts (**A1**–**A3**): **A1**. the *operational space* denotes the region of space that an object requires to perform its intrinsic function that characterizes its utility or purpose, **A2**. the *functional space* of an object denotes the region of space within which an agent must be located to manipulate or physically interact with a given object, **A3**. the *range space* denotes the region of space that lies within the scope of a sensory device such as a motion or temperature sensor,
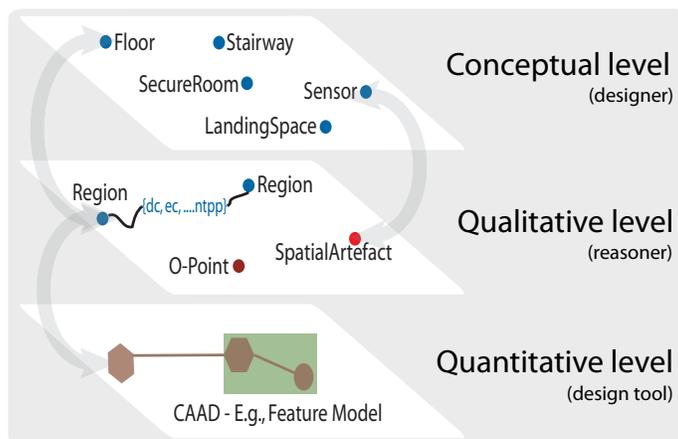
Figure 3. Multi-Perspective Semantics and Representational Modularity.

or any other entity capable of visual perception. Range space may be further classified into other categories, such as *observational space* (e.g., to model the concept of the *isovist*[5])

Figure 2 provides a detailed view on the different kinds of spaces we introduced. From a geometrical viewpoint, all artefacts refer to a conceptualised and derived physical spatial extension in $\mathbb{R}^n$. However, they do differ from an ontological perspective and the manner in which their geometric interpretations in $\mathbb{R}^n$ are derived. The derivation of an interpretation may depend on object's inherent spatial characteristics (e.g., size and shape), as well as additional parameters referring to mobility, transparency, etc.

Multi-Perspective Semantics & Representational Modularity.   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. This is what a designer must deal with during the initial design conceptualization phase. However, when these notions are transferred to a CAAD tool, the same concepts acquire a new perspective, i.e., now the designer must deal with points, line-segments, polygons and other geometric primitives available within the feature hierarchy of the design tool, which, albeit necessary, are in conflict with the mental image and qualitative conceptualization of the designer. Given the lack of semantics, at least within contemporary design tools, there is no way for a knowledge-based system to make inferences about the conceptual design and its geometric interpretation within a CAAD model in a unified manner.

As an example, consider a binary relation 'connects' that links entities from the conceptual, qualitative, and quantitative levels of Figure 3; a Floor at the conceptual level could be abstracted as a Region at the qualitative level of a reasoner, and as a ClosedPolygon at the quantitative level thereby preserving the geometry of a CAAD-based feature model. Bhatt et al. (2012) presents a complete axiomatisation of multi-perspective semantics for the spatial design domain.

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5. An isovist is the set of all points visible from a given vantage point in space and with respect to an environment (Benedikt, 1979).
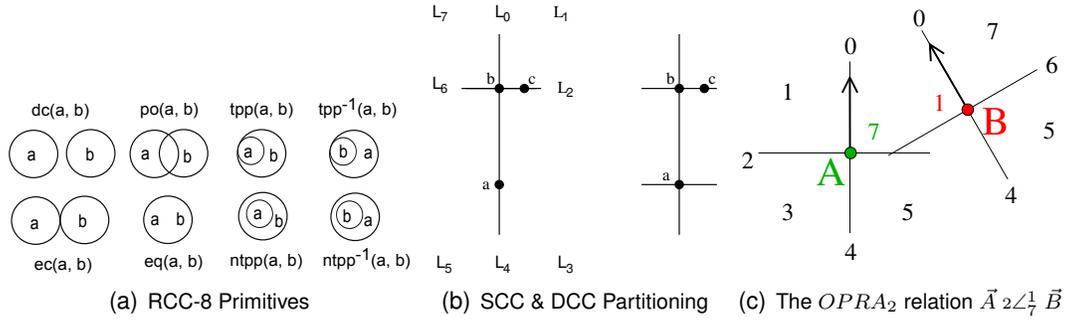
Figure 4. Topological and Orientation Calculi.

3.3 Spatial Representation and Reasoning

Research in Qualitative Spatial and Temporal Representation and Reasoning (QSTR) develops powerful representation formalisms that account for the multi-modality of space in a cognitively acceptable way (Freksa, 1991). QSTR abstracts from the metrical details of the physical world and enables computers to make predictions about spatial relations, even when quantitative information is not available (Freksa, 1991; Cohn & Renz, 2007). Using this approach, spatial information is represented using a vocabulary consisting of a finite set of spatial relationships that may hold between the primitive ontological elements, viz., *regions*, *points*, and *line-segments*, of the spatial domain. Furthermore, it is also necessary that spatial information representation formalisms be provided with formal semantics and that they allow for efficient reasoning or computational mechanisms (Renz & Nebel, 2007). In QSR, spatial information representation corresponds to the use of formal spatial calculi such as the Region Connection Calculus (Randell, Cui, & Cohn, 1992) (RCC), Single-Cross and Double-Cross Calculi (SCC, DCC) (Freksa, 1992), Oriented Point Relation Algebra (OPRA) (Moratz, 2006) (see Figure 4). Formalizations (logical, relational-algebraic) of space and tools for reasoning with spatial and temporal information are now well-established (Renz & Nebel, 2007; Bhatt et al., 2011).

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. Therefore, a very important goal in analytical design computing is to formally and computationally investigate the link between structural forms, as denoted by specific spatial configurations of domain entities (or more generally, by the "*the shape of empty space*" (Bhatt, Schultz, & Huang, 2012), and the behaviours / (mal)functions that they are inherently capable of producing with respect to a pre-specified set of requirements conceptually expressed by an architect or a designer.

Artefactual Constraints, Structural Form and Design Function. Spatial artefacts such as those introduced in (**A1**–**A3**) are usable towards formulating functional requirement constraints for a work-in-progress spatial design. Constraints, emanating from the requirements such as in in (**R1**–**R3**; Section 2) may need to be satisfied by a design:
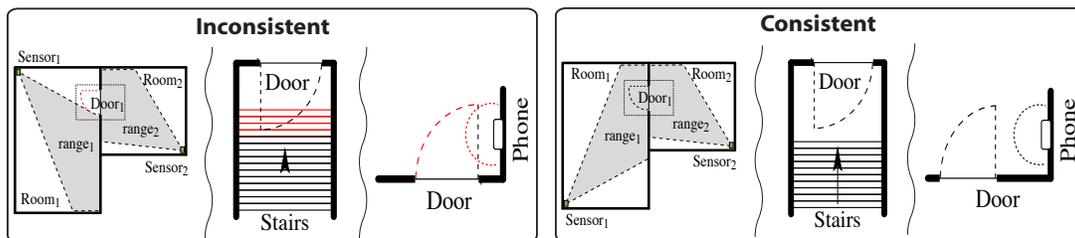
Figure 5. Design Requirements: Example Spatial Interpretations.

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

C2. The StairWay should be topologically non-overlapping with the FunctionalSpace and OperationalSpace of other entities

C3. People should not be harmed by Doors opening up. In general, the OperationSpace of a Door should be non-interfering, i.e., not overlap with the function / operation (i.e., functional/operational space) of surrounding objects.

The schematization in Figure 5 is a continuation of the example requirements introduced in (**R1**–**R3**), and semantically expressed constraints in (**C1**–**C3**). To consider one of the three consistent/inconsistent cases from Figure 5, namely (**C1**, **C3**), below is a semantically grounded semiformal representation of a requirement constraint:

C3.	**Class**:	qualitative_level:PhoneFunctionalSpace
	SubClassOf:	qualitative_level:FunctionalSpace,
		not (space:topology:overlaps
		some (qualitative_level:DoorOperationalSpace))

The remaining example from Figure 5, corresponding to (**C2**), too may be modelled in a similar manner, namely, as a topological constraint among the primitive conceptual / qualitative / quantitative entities within the design model. Clearly, there are many more possibilities to model requirement constraints on the basis of other aspects of space, e.g., orientation, cardinal directions, metric / fuzzy distances. In this manner of modelling, it must be emphasised that the resulting functional consistency is interpreted strictly with respect to the structural form of the design.

3.4 Design Intelligence – Modes of Inference

The term design intelligence is rather open and subject to diverse interpretations; its scope and definition are only limited by the range of the inference patterns that may be operationalised computationally. From the viewpoint of this paper, we have rather specific inclinations with respect to the reasoning capabilities that must be the focus of analytical design computing.

Conceptual Reasoning. Conceptual reasoning corresponds to the ontological reasoning patterns that are available within the framework of a terminological reasoning system grounded to the se-
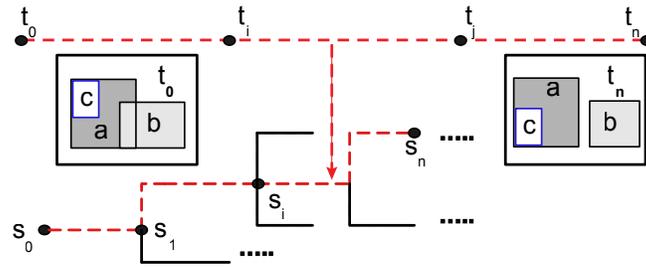
Figure 6. Branching / Hypothetical Situation Space. Source: (Bhatt, 2012)

mantics of a *Description Logic* (DL) (Baader et al., 2003). Ontology reasoning systems such as RACER (Haarslev, Möller, & Wessel, 2004), PELLET (Sirin et al., 2007) support typical DL inference tasks at the *terminological* (subsumption, satisfiability, equivalence, disjointness) and *instance* levels (instance checking, data consistency, realisation, retrieval). For example:

1. *Retrieval task*: identify all concrete entities / geometric features (e.g., '*polygons*') from instance data coming from a CAAD model that correspond to a design abstraction / artefact such as 'FunctionalSpace' or 'MovableEntity'

2. *Instance checking*: given a set of geometric features within a CAAD model, what is the most general / specific abstract ontological category that the identified feature belongs to from the conceptual / artefactual viewpoint of the designer

From a conceptual reasoning viewpoint, another important reasoning task is determining whether or not the requirement constraints, functional or otherwise, specified by a designer may possibly be satisfied by a model per se. 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.

Functional Consistency. The example scenarios in Section 3.3 illustrated the extent and manner in which functional requirement consistency may be modelled with respect to the structural form of design. This is the form of consistency that has been discussed and illustrated throughout this paper. However, the notion of functional consistency transcends beyond the purely spatial aspects of a design, and also includes semi-spatial aspects that include the material and constitution of design artefacts, aspects such as weight, colour, physical characteristics, and artistic aspects that may be beyond the domain of space. Regardless of precisely what these aspects are, the inference patterns required to ensure functional consistency, in so far as it is formalisable, is essentially some form of constraint reasoning approach over a spatial or non-spatial domain, which is the forte of the state-of-the-art in AI research (see Section 4).

Hypothetical Reasoning. Reasoning about conceptual & functional consistency is only a starting point: for design analytics, the real challenge is to not only reason about not what is, but also about what could be. This form of inference is referred to as *hypothetical reasoning* (Bhatt, 2012). In general, within a decision-support or design assistance tool, metrical changes in the structural layout or changes in the relative spatial relationships of the design elements – i.e., qualitative changes along the conceptual space of the designer – will directly or indirectly entail differing end-product
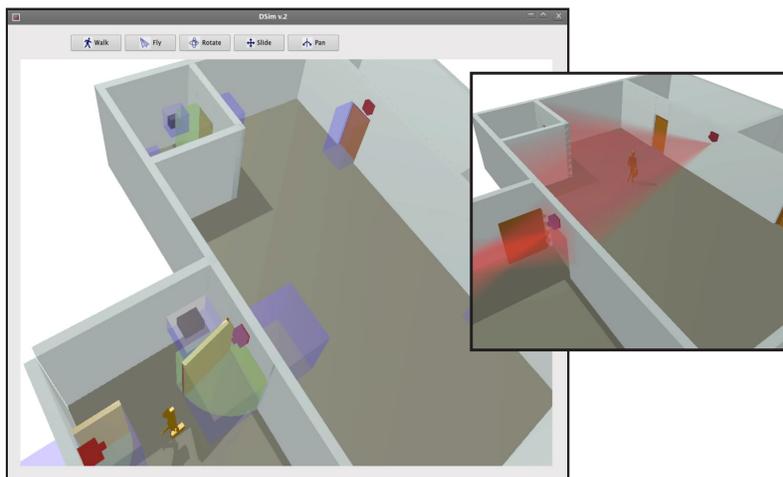
Figure 7. 3D realizations of the *functional*, *operational*, and the *range* spaces of the architectural entities. **System DSim** (Bhatt, Ichim, & Flanagan, 2010)

realizations in terms of spatial design requirements, building construction costs, human-factors (e.g., traversability, wayfinding complexity), aesthetics aspects, and energy efficiency and long-term maintenance expenses thereof. As such, commonsensical and hypothetical reasoning at the qualitative level about *physically realizable*[6] and functionally consistent structural forms represents a solution approach that is useful for providing the designer with creative design recommendations.

By not discretizing the space and considering the full range of quantitative possibilities, the problem of hypothetical reasoning is, in full generality, infinitesimal and intractable. However, alternate recommendations are derivable by hypothesising the potential spatial re-configurations / transformations (e.g., by translation and deformation actions) at a qualitative level. As an example, consider the illustration in Figure 6. The situation-based history $< s_0, \ s_1, \ldots, \ s_n >$ represents one path, corresponding to an actual timeline $< t_0, \ t_1, \ldots, \ t_n >$, within the overall branching-tree structured situation space that could be representative of a space of design evolutions at the qualitative level. Therefore, the objective of hypothetical reasoning about the '*design space*' is to infer / hypothesize (e.g., by abductive reasoning) physically plausible qualitative variations in a design that are also essential or functional requirement fulfilling. Indeed, hypothetical reasoning may also take into consideration domain-specific heuristics / physical attributes that determine aspects such as movability, deformability, stability. Such a logic-based approach could also work as a complementary technique to other approaches such as *generative design computing*, whereby stochastic generative processes may be guided by high-level semantic design constraints and requirements.

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6. The commonsensical notion of a *physically realizable situation* defined in terms of physical, compositional and existential consistency of spatial situations (Bhatt, 2012). Also, see the treatment of aspectualization for architectural design in (Bertel, Freksa, & Vrachliotis, 2004)

3.5 Assistive Feedback Mechanisms – Design Simulation

Assistive feedback mechanisms by visualisation and simulation have to be provided in order to communicate diagnostics and other forms of design support within a conventional CAAD workflow. Conventional CAAD tools have remained focussed on providing capabilities for aesthetically appealing 3D visualisation of floor-plans. State-of-the-art tools also allow easy placement / visualisation of third-part 3D models of common interior artefacts, thereby enhancing the 3D visualisation experience. The human-computer interaction aspects involved in the communication and interaction between a designer and next-generation CAAD tools is an open topic of research. It is not our objective here to speculate on the future directions of this field of research. The visualisation and simulation aspects pointed out in the following are some benchmarks that have been set for our working prototype DSim (Bhatt, Ichim, & Flanagan, 2010). As a prototype, DSim attempts to operationalize the concept of being able to "*live your design*"[7]: (**a**). *Semantic browsing* vis-à-vis the structural hierarchy of the design, (**b**). Real-time spatial *artefact simulation* (e.g., sensors, camera; see Figure 7), (**c**). *Inconsistency pinpointing* at the structural and semantic level, (**d**). Hierarchical and *selective zooming* for specific requirements, and (**e**). Automatic *reconfiguration and placement* of design artefacts.

We consider these features to be crucial and necessary for next-generation CAAD tools that not only support the 2D / 3D spatial modelling, but also provide the conceptual spatial modelling and functional reasoning capabilities, such as those described in this paper.

4. Discussion and Summary

Our notion of assistance-driven analytical computing for (spatial) design is firmly grounded in the AI / KR-centred perspective, which we regard to be emanating from the Herbert Simon's original articulation of the *Science of Design* (Simon, 1969; Simon, 1996). Gero (1991) positioned "*Ten Problems for AI in Design*". With respect to the scope of this paper, we relate to some of them:

- Representation in design, design semantics – "*What is it that the designer knows and how do we get a computer to know it?*"
- Inference in design – "*much of design inferencing has to do not only with deductive inference but with abductive inference which is concerned with what might be rather than what is*"
- Combinatorial explosion in design – "*as soon as a system deals with what could be it could go on indefinitely*"

The problem of representation in design and design semantics is related to the modelling of *multiple perspectives* and the explicit representation of requirements as per their conceptualization by a designer. The problems of reasoning about what could be and combinatorial explosion in design are two sides of the same coin: hypothetical reasoning within a qualitative context (by abduction or otherwise), under additional constraints of physical realizability and architecture domain-specific heuristics poses interesting challenges that merit further treatment.

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7. **System DSim**.   http://tinyurl.com/system-dsim

Much has changed in AI since the early 90s. Frame-based systems and semantic networks have evolved into a range of description logic based ontology languages that are tailored to different levels of expressivity and computational properties (Baader et al., 2003). Practical ontology reasoning systems such as *Racer* (Haarslev, Möller, & Wessel, 2004) and *Pellat* (Sirin et al., 2007) have also come to the fore. The evolution of Logic Programming (LP) to Constraint Logic Programming (CLP) (Jaffar & Maher, 1994) and other powerful computational embodiments of the default and non-monotonic reasoning paradigms by way of Answer-Set Programming (ASP) (Vos, 2009) are developments that have only found limited attention in the design community. The field of qualitative spatial representation and reasoning has emerged as a new sub-discipline within knowledge representation – specialized spatial reasoning systems *CLP(QS)* (Bhatt, Lee, & Schultz, 2011), *SparQ* (Wallgrün et al., 2007) and *GQR* (Westphal, Woelfl, & Gantner, 2009) now support spatial reasoning and additional application-support services that make it possible to model and reason about spatial knowledge in ways that have not been possible before.[8] These developments open up interesting new possibilities and programming paradigms not only for solving design problems hitherto considered to be computationally intractable, but also for integration, in fundamental ways, of generalised logic-based reasoning on the one hand, and specialized spatial reasoning techniques on the other (Bhatt, 2012).

The progress made in the last two decades within the knowledge representation and reasoning community in general, and the field of spatial reasoning in specific, warrants a re-visitation into the '*design as problem-solving*' approach of Simon (1969). In spite of garnering initial momentum and interest in the 'AI for Design' community, this approach initially failed to make an impact by way of practical industrial applications. This paper is partly a statement of our work-in-progress, and partly an attempt to revive some of the basic questions underlying AI in / for design computation in general, and for spatial cognition and computation for design in particular.

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8. The spatial reasoning system CLP(QS) (Bhatt, Lee, & Schultz, 2011) offers geometric and qualitative spatial abstraction and reasoning capabilities within a Constraint Logic Programming setting; the SparQ (Wallgrün et al., 2007) spatial reasoning toolkit provides a relational algebraic characterisation of specialized spatial reasoning services.

We now use the notion 'spatial computing' in a more specific sense (Freksa, 2013); therefore the paper has slightly changed. In addition to changes in the content, we have also updated the article with citations to recent research conducted to advance the prototypical perspectives presented in this article back in 2010. Detailed reports are available in (Bhatt, Lee, & Schultz, 2011), (Schultz & Bhatt, 2012), (Bhatt, Hois, & Kutz, 2012; Bhatt, Schultz, & Freksa, 2012; Bhatt, Schultz, & Huang, 2012).

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