A Multi-Modal Data Access Framework for Spatial Assistance Systems

Use-Cases with the Building Information Model (BIM / IFC)

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ABSTRACT

Spatial assistance systems are computational embodiments of spatial decision-making and other forms of analytical abilities that otherwise typically require extensive domain-specific training, knowledge, and expertise. Broadly, such systems are essentially instruments of *assistance*, *assurance* and *empowerment*. Whereas these systems may vary in the domain of application and the precise manner of intelligent assistance, there exist several fundamental similarities from a systemic and information-theoretic viewpoint with regard to the ontological and computational foundations that underlie their practical design and implementation.

We present a multi-modal spatial data access framework designed to serve the informational and computational requirements of the class of spatial assistance systems that are intended to provide intelligent spatial decision-making capabilities. The framework focuses on multi-perspective semantics, qualitative and artefactual abstractions, and industrial conformance and interoperability. We position the framework, and also provide use-cases with distinct application domains.

Keywords

spatial data models, spatial computing, ontology, semantics, indoor environments, spatial assistance, decision-support systems, interoperability

1. INTRODUCTION

The key objective of assistance systems, be it spatial or otherwise, is essentially to transfer the cognitive stress involved in an analytical activity onto a system, by externalising and operationalising the decision-making processes involved therein. In essence, *Spatial Assistance Systems* (SAS) are computational manifestations of the spatial and situational awareness capabilities of individuals and groups, who may potentially be experts in a particular area of interest. Given the scope of this paper, which is focussed on computational systems requiring spatial awareness capabilities, some examples of assistance systems include decision-support tools that require specialized *Spatial Computing* capabilities:

▶ *Architectural Design Assistance.* Systems where a work-in-progress design of a building within the context of a Computer-Aided Architecture Design (CAAD) tool has to be reasoned about.

▶ *Real-Time Emergency Assistance.* Systems that provide assistance for emergency scenarios such as firefighting, rescue, evacuation and so forth.

▶ *Indoor Navigation Assistance.* Systems that provide specialised way-finding and navigation support mechanisms for built-up environments such as Malls, Exhibition Centres, Museums, Air-Ports and so forth.

▶ *Ambient Assisted Living (AAL).* Practical systems aimed at serving an empowering and assuring function within private spaces such as residences, private offices and so on. Typically, these systems involve interactions between humans, robots and software systems.

▶ *Pervasive and Ubiquitous Computing (UbiComp).* These include a broad range of technologically-driven systems involving the modelling of, for instance, situational context and the semantics of space and place within mobile and location-based services, systems of activity modelling and analysis and so forth.

The range of assistance capabilities, e.g., by way of intelligent decision-support, data analysis, artefactual simulation, virtual reality, that may be operationalised over quantitive descriptions of real or hypothetical indoor spatial environments is rather exhaustive, if not infinite. Central to these categories of systems is a common foundational basis consisting of representational modalities and computational capabilities:

- from a *representational viewpoint*, modalities for semantic modelling, multi-perpective representations, and qualitative spatial abstractions acquire a central significance
- from a *computational viewpoint* and closely connected to the representational modalities, computational techniques for conceptual and qualitative (spatial) reasoning that define the essential character and nature of the analytical and assistive capability being implemented

Furthermore, whereas there exist distinct categories of spatial assistance systems, and additionally, inherent differences between descriptions of indoor spatial environments and those of open environmental spaces, the fundamental capabilities for spatial computing (e.g., for spatial awareness) in the context of a *Structured Spatial Environment* (SSE) and the information requirements for the range of assistance systems bear close relationships and similarities [Bhatt and Freksa, 2010]. For the case of indoor or built-up environments, and for spatial assistance scenarios such as those aforementioned, it may be presumed that geometric model(s) of the environment under consideration environments are available, e.g., by way of accurate building and floor-plans (CAAD, design assistance), graph-based models (way-finding assistance), CFD-based finite-element models (structural analysis, cost estimation, phenomenal studies to simulate fire spread). These models may pertain to real spatial environments that have been built (e.g., a Museum), or they may pertain to an arbitrary environment that is undergoing initial conceptualisation, prototyping, and design. Spatial computing (for spatial awareness), however be it defined from a cognitive, ontological and computational viewpoint, does not differentiate between real and hypothetical environments. That is, different types of analytical capabilities that may be deemed to be within the purview of a particular interpretation of spatial awareness have to be based on high-level quantitative and qualitative perspectives that are grounded to a geometric model of the concerned environment. Furthermore, it is desired that these models of SSEs be grounded to industrial data representation standards designed for community-wide (tool) compliance and interoperability.

In this paper, we present a high-level, semantic spatial data access framework for the specialized domain of indoor spatial environments. The framework provides conceptual and qualitative spatial abstraction capabilities over geometric spatial data pertaining to indoor environments, and is suited for a wide range of spatial assistance systems. Of specific interest to the application aims of our work is conformance with industrial standards for the representation of built-up spaces. In this context, we ensure interoperability with commercial tools concerned with the creation, manipulation and management of environmental data by utilising the stipulations of the Building Information Model (BIM) [Eastman et al., 2008] and the Industry Foundation Classes (IFC) [Froese et al., 1999].

2. MULTI-MODAL SPATIAL DATA ACCESS

Spatial computing for assistance systems involves an interplay between information-theoretic computational models of spatial data and the conceptual and cognitive perspectives of users of assistance systems [Bhatt and Freksa, 2010]. For e.g., in the case of design assistance systems, 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* [Bhatt and Freksa, 2010, Bhatt et al., 2010a].

Our proposed framework focusses on multi-modal spatial data access capabilities that provide a range of data access modalities including *multi-perspective semantics*, *qualitative abstractions*, and *artefactual querying* among others. The emphasis is on providing high-level, multi-modal spatial data access in an industry complaint and interoperable manner.

2.1 Structural Form of an Environment

The *structural form* of an environment is an abstraction mechanism generally corresponding to the layout, shape, relative arrangement and configuration of spatial entities, artefacts, and anything else — abstract or real — that may be geometrically modelled, interpreted or derived.

At a formal level, our notion of structural form is closely rooted in the abstraction, representation and computational mechanisms in the field of Qualitative Spatial Representation and Reasoning (QSR). QSR is an established field of research investigating qualitative representations of space that abstract from the quantitative details of the physical world together with reasoning techniques that allow predictions about spatial relations, when precise quantitative information is not desired or available [Cohn and Hazarika, 2001]. QSR includes investigations of human understanding of space, qualitative representations of different spatial aspects (e.g. orientation, topology, size), and mathematical properties of operations for manipulating and combining the represented knowledge. A qualitative description is one that captures distinctions that make an important, qualitative difference, and ignores others.

For the purposes of this paper, the structural form may be interpreted as a constraint network that determines the relative qualitative spatial relationships between the real and artefactual entities contained within a design. The spatial relationships themselves are grounded to the vocabulary of a formal *qualitative spatial calculus*.[1] The spatial data access framework provides an interface to qualitative information that may be used by specific high-level reasoning modules within a spatial assistance system.

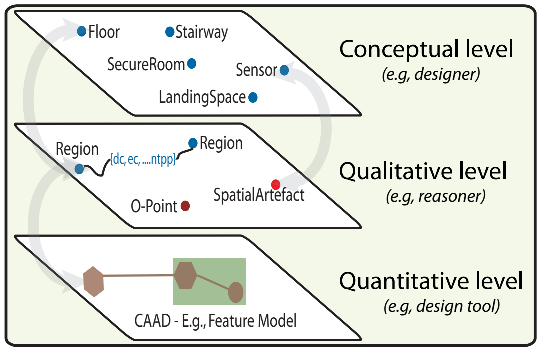

Figure 1: Multi-Perspective Semantics

A. Multi-Perspective Semantics

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. For instance, a Floor at the conceptual level is abstracted as a Region at the qualitative level of a reasoner and as a ClosedPolygon thereby preserving the geometry at the quantitative level of a CAAD-based feature model (Fig. 1). Multi-perspective semantic modelling is needed for a knowledge-based system to make inferences about the conceptual design and its geometric interpretation within a CAAD model in a unified manner.

[1] A qualitative (spatial) calculus constitutes a formal framework for spatial information representation and reasoning, typically with relational algebraic semantics [Ligozat and Renz, 2004].

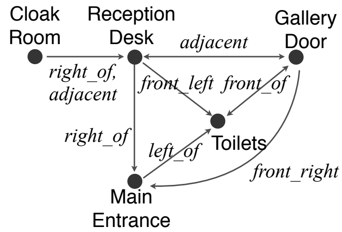

Figure 2: QvGraph of a museum lobby.

B. Qualitative Characterizations

The framework presently supports the following types of qualitative information access capabilities:[2]

▶ *QvGraphs.* We define and derive *Qualitatively Annotated Visibility Graphs* (QvGraphs) as an extension to the concept of a *Visibility Graph* [Lozano-Pérez and Wesley, 1979, de Berg et al., 2000]. In computational geometry, a visibility graph of a polygonal scene shows the intervisibility relations between a set of points (locations, obstacles etc) in a scene, as geometrically constituted within the Euclidean plane. In a visibility graph, nodes 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, distance. Figure 2 illustrates an example of a visibility graph of a museum lobby.

▶ *Route Graphs.* A route graph, as defined in [Werner et al., 2000], corresponds to a cognitively and linguistically motivated spatial representation of an environment that focuses on qualitatively capturing different routes an agent can use for navigation [Werner et al., 2000]. The derivation of such navigational knowledge for the case of built-up spaces is an important facility provided by our data access framework.

▶ *Flow Vectors.* While route graphs can model the general notion of movement and flow at a high-level between spaces, often application tasks require the modelling of more localised movement within a space such as airflow within a room. This localised flow is modelled using flow vectors [Kowadlo and Russell, 2006]. In our data access framework, a flow vector is defined as a rectangle with a direction (see Section 4.1.2).

▶ *Hierarchical Models.* The data access framework provides access to a *hierarchical* and *multi-domain* model of space that is suited to solving representation and reasoning problems that arise within the context spatial assistance systems.[3] From the viewpoint of hierarchization, the aim of this work is to develop an organization of qualitative spatial information that splits the related entities into independent subsets and allows for solving spatial reasoning tasks at an adequate level of granularity. The resulting hierarchical representation should support the same reasoning and design tasks that would be possible with a flat qualitative representation but do so in more efficient and intuitive way.

C. Spatial Artefacts

A key aspect of domain-specific reasoning focuses on the interaction between people and objects, and primarily object utilisation and behaviour [Bhatt et al., 2009]; e.g., *Is an information terminal sufficiently prominent and accessible to people entering the foyer of the museum*? Likewise, *as the door is opened, is there a potential risk of injury*? *Is the spot light directed appropriately in order to highlight the piece of art*? Addressing these types of queries requires reasoning about aspects of objects beyond the geometry of the physical body. These additional aspects of objects are referred to as *spatial artefacts* [Bhatt et al., 2009] and are divided into three principal categories:

▶ Functional space: regions of space within which a person must be located in order to interact with the object or to employ the object for its intended function (e.g. the region surrounding an information kiosk, or the occupancy areas in a lecture theatre where a whiteboard is adequately visible)

▶ Operational space: regions of space that an object requires to perform its intended function (e.g. the region of space occupied by a door as it opens)

▶ Range space: regions of space that the object operates on as a result of performing its intended function (e.g. the scope of a surveillance camera, the regions illuminated by a light source)

Our framework incorporates spatial artefacts into the environmental model in a uniform manner; similar to the physical body of objects, each spatial artefact is represented by a geometric placement and shape representation. Formally, the placement and geometric shape of spatial artefacts is a function of the object, the surrounding physical environment, and the action being performed on the object.

2.2 Interoperability, Industrial Conformance

Our multi-modal spatial data access framework is grounded partly in industry design practices and standards such as the Building Information Model [Eastman et al., 2008], Industry Foundation Classes [Froese et al., 1999] and professional CAAD design tools such as ArchiCAD [Graphisoft Inc., 2010]. The IFC is a non-proprietary data exchange format that represents building, construction and architectural design information. IFC was developed in response to the need for more domain-specific models, and to foster interoperability in the construction IT industry. Importantly, IFC incorporates domain knowledge by defining objects classes such as walls, door, and windows and the inherent relationships between object classes; numerous geometric primitives are also defined such as points, lines, and polygons for representation geometric information about the placement and shape of objects. Commercial design tools such as Graphisoft's ArchiCad [Day, 2008] support IFC export capabilities and a range of free software tools exist for modeling, visualizing, and validating IFC data. As our approach utilizes IFC data, datasets from any IFC compliant design tool remain utilizable.

3. SPATIAL DATA ACCESS FRAMEWORK

In this section we establish our framework for deriving and augmenting building models from IFC in order to facilitate qualitative reasoning. Figure 3 presents an overview of our framework.[4]

[2] We have omitted formal definitions of the elements within the *structural form* as the main aim of this paper is to provide an overview of the capabilities of the framework.

[3] The model is described in a technical report [Bhatt et al., 2010b] that is available upon request.

[4] Solid boxes represent data and model representations, ellipses represent functional units, the data representation components of our framework are within the large dotted rectangle, the rounded rectangle represents the process for parsing from IFC into our framework's data representations, and arrows represent the flow of information.

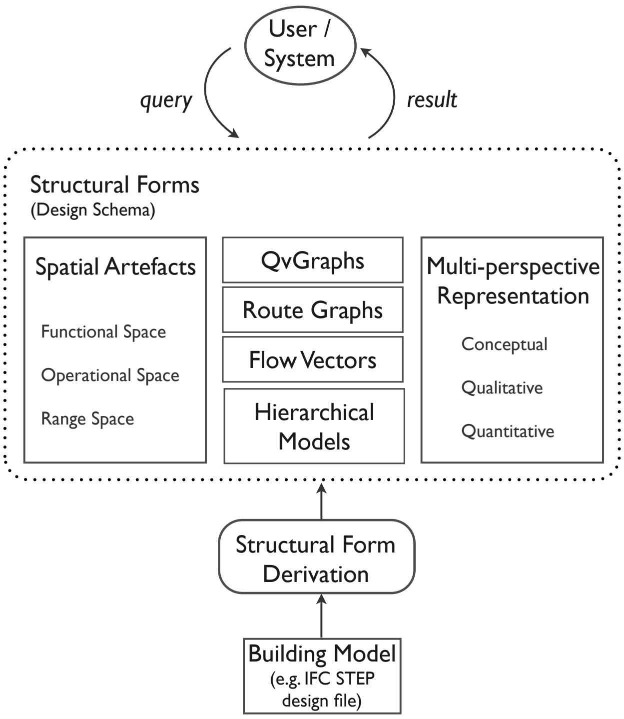

Figure 3: Spatial Data Access Framework

3.1 Automated Structural Form Derivation

We have implemented a prototype tool for converting an IFC design file into a model that is amenable to qualitative reasoning. The key stages are:

1. parsing the IFC design file into a 2D floor plan by extracting the salient geometric and relational design information

2. deriving structural forms, which in so far as this paper is concerned, encompass features such as geometric placement and shape representations of spatial artefacts, and qualifying the geometric data to derive qualitative spatial relations relevant to QvGraphs and route graphs

IFC is a large and comprehensive building data model that aims to encompass all aspects of building design and construction including cost management, construction logistics, life-cycle management and so on. The aspects of IFC that are of primary significance for qualitative reasoning are IFC objects and key IFC relationships between objects.[5]

The two key features of objects that require parsing are placement and shape representation information. We define placement as a translation and a rotation of the object's origin and direction, which is extracted from the object's unique placement information and the object's placement relative to other objects. An object's shape representation is defined as a one-piece regular region bounded by a closed polygon representing the object's schematic footprint on a floor plan.[6] In IFC design files the geometric representations of rooms and other spaces are typically specified as 2D footprints which are vertically extruded; in these cases we simply use the 2D footprint as the representation of the parsed object in our framework. Other smaller objects such as doors and furniture are typically represented in IFC files using more complex Brep representations; in these cases we extract representation data by collecting the set of points that define the 2D or 3D shape, projecting the points onto the 2D plane parallel to the floor, and then taking the convex hull of the 2D point cloud.

In general, the IFC relationships that are necessary for qualitative reasoning are between two sets of objects. For example, aggregation (*IfcRelAggregates*) is between one *relating* object and a set of *related* objects that decompose the relating object. Determining whether a relationship is parsed requires checking that the relationship type is supported, and checking that at least one *related* object and at least one *relating* object are supported.

When certain IFC relationships are not parsed it is often necessary to introduce new relationships to ensure that the parsed design is consistent. For example, in IFC the concept of holes (*IfcOpeningElement*) are used to embed doors and windows into walls and other objects; that is, given a wall w, door d, and a hole h, then *IfcRelVoidsElement(h,w)* and *IfcRelFillsElement(d,h)*. For the qualitative reasoning that is currently required it is sufficient to relate the wall and the door directly without introducing the more sophisticated notion of holes. Thus, every instance of this IFC combination of relationships with holes must be replaced by a new relationship $RelContains(d, w)$.[7]

3.2 Querying Structural Forms

The queries that application users need to specify do not typically refer to geometric information directly, and instead refer to qualitative, domain specific concepts. Being able to specify these more abstract qualitative queries requires alternative perspectives of a building design that incorporate domain knowledge beyond the purely geometric structural information.

The different perspectives of a building design that a user requires are organised into modules as illustrated in Figure 1. Qualitative spatial relations such as *externally connected* and *left of* are defined directly with respect to the

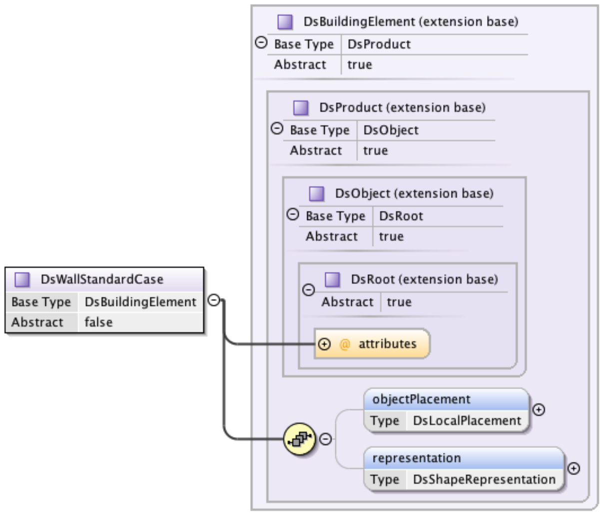

Figure 4: Extract of the Indoor Space Modelling Schema.

[5]The corresponding IFC classes are IfcProduct and IfcRelationship.

[6]The two currently supported IFC representation types are swept solid (extrusion) and Brep.

[7]Other examples include ensuring that aggregation (*IfcRelAggregates*) and containment (*IfcRelContainedInSpatialStructure*) hierarchies are maintained when particular objects in the hierarchies are not included in the parsed design.

underlying geometric data.[8] More general qualitative concepts are defined using combinations of qualitative spatial relations and geometric information.
Importantly, certain qualitative concepts are shared by a wide variety of different application domains. For example, the apparent *flow* of an environment is how the layout, lighting, and other design features guide and direct the attention of a person as they enter a room. This very versatile intermediate qualitative concept is critical to notions of:

- way-finding e.g. directing people towards fire escapes during emergencies;
- aesthetics e.g. enhancing the impact of a masterpiece in an art gallery as a person enters the room [Cuttle, 2003];
- managing crowds (e.g. using lighting to guide people through a museum in a manner that avoids congestion).

It must be noted that qualitative concepts often have multiple definitions, and the appropriate definition is determined by the application context. Similarly, way-finding, which is defined using intermediate qualitative concepts, is a very versatile concept that is also used in a variety of application domains such as architectural design, emergency rescue and so on. Thus, the qualitative conceptual module can be divided into three parts:

- reusable intermediate qualitative concepts such as ambient *illumination, accessibility, visibility, symmetry*, and apparent *flow*,
- reusable higher-level qualitative concepts such as way-finding, subjective impressions and security, and
- specific application domain concepts.

We are primarily concerned with identifying highly versatile intermediate qualitative concepts that are critical to a wide range of application domains.

4. CASE STUDIES IN DATA ACCESS

We present two case studies to exemplify the versatility of the multiple spatial data access modalities provided by our proposed framework.

4.1 Real-time Emergency Assistance

Spatial assistance systems allow rescue workers to combine computer models with real-time sensor data to predict the behaviour and spread of hazardous gases and fires in indoor environments. This can provide emergency rescue personnel with the information needed to evacuate injured occupants and to mitigate or eliminate the risk of further damage and loss of life.

Emergency scenarios require extremely fast response times from computational models, often in the order of seconds and minutes. Numerical models and simulations for predicting the spread of fire and gasses are often too time consuming and complex [Kowadlo and Russell, 2006]. Moreover, the data necessary to execute sophisticated simulations may not be available such as the velocity of a gas, the precise time that a gas started to leak, the precise location of the source of the leak and so on. To address this, qualitative models have been proposed to balance the tradeoff between computing the necessary information with the available data and the time required for reasoning [Kowadlo and Russell, 2006].

[8]This process is called qualification and can also depend on domain knowledge and the application context.

Example 1 (Gas Leak at a Factory) A minor earthquake has ruptured a chemical container located in the storage warehouse of a factory. The rupture has caused the emission of noxious gas fumes into the warehouse, which have escaped through a ventilation system and have spread to other regions of the factory. Firefighters will be arriving at the factory site within minutes and thus have very limited time to develop a plan of action. They have detailed CAAD plans of the building and they are equipped with the appropriate instruments for detecting and measuring the local presence of the fumes. Their first task is to enter the building, search for and evacuate injured occupants, and manually secure the appropriate regions of the factory in order to stop the continuing spread of the hazardous fumes. Their second task is to enter the storage warehouse, identify the source of the gas, and contain the leak. □

4.1.1 Fume Diffusion

The first task requires the spatial assistance system to model gas diffusion. This will allow the firefighters to determine the regions of the building that the gas is likely to have spread to.

Example 2 (Room Connectivity) Given that *gas* spreads through space in a continuous fashion, the gas diffusion can be modelled using a connectivity graph of rooms and spaces. Each IFC space (e.g. a room or an open area) is represented as a vertex. If a gas can travel directly between two spaces s_1 and s_2 then the spaces are considered to be adjacent, represented by a graph edge between the two corresponding vertices. A space typically has multiple points of entry that may be significantly spatially distributed. Thus, the connectivity graph must include one edge for every combination of entry points into s_1 and transition points between s_1 and s_2. □

Example 3 (Dispersion Impedance Values) Using the methodology presented in [Li et al., 2009], the edges of the connectivity graph are annotated with impedance values that can be used to calculate the time required for a gas to spread from one space to an adjacent space. If the gas is travelling at velocity v then the minimum time needed for a gas to travel from space s_1 at entry point e_1 to space s_2 via entry point e_2 is the time required to cover the shortest path from e_1 to e_2 (which can be admissibly approximated as a straightline). Thus, the impedance value d is the distance of the shortest path between the two entry points. The minimum time t required to travel between spaces is $t = d/v$. □

Using the connectivity graph the firefighters can determine the entry points of the fumes into the other regions of the building by identifying spaces that are directly connected to the ventilation system. The firefighters also know the time of the earthquake and thus have an approximate earliest time that the leak occurred. Given an expected dispersion velocity based on the chemical type, the firefighters can use the spatial assistance system to approximately determine the regions of the building that potentially contain the noxious gas, thus enabling the firefighters to rapidly develop a plan of action to evacuate injured occupants and secure the fumes.

4.1.2 Local Fume Dispersion in the Warehouse

The second task is to contain the fumes at the source of leak in the storage warehouse. This methodology is adapted from the approach presented in [Kowadlo and Russell, 2006]. The warehouse storage area is a large rectangular room with a number of large objects, any one of which could be the potential source of the fumes. This is a very hazardous environment that may contain volatile substances which could react with the chemical fumes. Thus, it is imperative that the firefighters spend as little time as possible identifying the source and containing the leak.

Rather than exhaustively visiting and analysing all objects in the warehouse, the spatial assistance system can use qualitative models about gas dispersion combined with real-time sensor data to determine which object is the most likely source. However, the problem of modelling the fume dispersion is complicated by the presence of airflow between the inlet and outlet of the ventilation system. In order to model the expected fume trace the spatial assistance system must first model airflow and plumes.

Definition 1 (Flow Vector) Flow vector f connects with another object x by being either directed towards of away from x,

$$ConnectsTo(f, x) = EC(f, x) \wedge Facing(f, x),$$
$$ConnectsFrom(f, x) = EC(f, x) \wedge FacingFrom(f, x)$$

where EC is the RCC8 relation *externally connected*, and $Facing$ and $FacingFrom$ relations are qualitative oriented point relations.

Given a reference region p lying on the flow vector body, the region from p to the head of the flow vector is the region *upwind* from p, and the region from p to the tail of the flow vector is the region *downwind* from p. □

Given sensor data and CAAD design files that describe the warehouse room with obstacles and a ventilation inlet and outlet, the airflow flow vectors can be automatically generated by the spatial assistance system according to a simple predefined algorithm such as the one developed in [Kowadlo and Russell, 2006]. The resulting airflow model can then be checked for consistency, and possibly revised if needed, using qualitative rules that specify airflow behaviour. The qualitative airflow model of the warehouse is illustrated in Figure 5; the boxes represent large containers that are potential sources of the leak, the dashed arrows represent the flow vectors, the dark grey rectangles represent the inlet and outlet of the ventilation system, and the grey clouds represent the salient portions of the expected fume traces.

Example 4 (Qualitative Airflow Behaviour) Eight qualitative rules for modelling airflow are presented in [Kowadlo and Russell, 2006]. These can be formalised in the spatial assistance system in order to check the consistency of an airflow model. For example,
"*Air movement continues unless impeded*"

$$\forall f \in airflow.FlowVectors, \exists x, y \cdot ConnectsTo(f, x) \wedge ConnectsFrom(f, y)$$

"If impeded, the air stream bifurcates, and travels parallel to the obstructing object in both directions"

$$\forall f \in airflow.FlowVectors, \exists x \in Obstacles \cdot ConnectsTo(f, x) \rightarrow (\exists f' \in airflow.FlowVectors \cdot (AttachedOnLeft(f', x) \vee AttachedOnRight(f', x)) \wedge ConnectsFrom(f', f))$$ □

The next step is to model the expected fume traces for each object that is a potential source of the leak. The fume traces are illustrated in Figure 5 as grey clouds that follow specific portions of the airflow flow vectors.

Example 5 (Fume Traces)
Fume traces are represented as geometric regions (i.e. fume.Body). Fume traces follow the flow vectors of airflow, and are thus generated automatically by taking the geometric rectangles of the flow vectors. Firstly the fume traces will follow all flow vectors $f \in airflow.FlowVectors$ directly touching the source object x,

$$fume.Body \supseteq \bigcup_{EC(f,x)} Downwind(f, p)$$

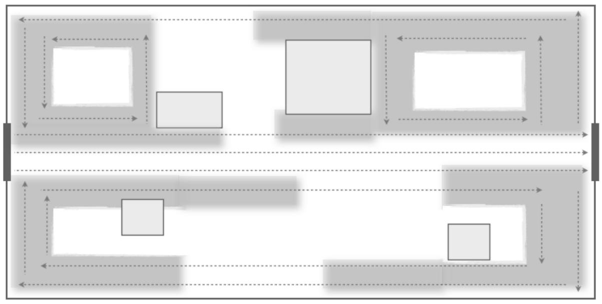

Figure 5: Airflow model and expected fume traces in the warehouse.

where p is the reference region formed by projecting x onto the flow vector body. Secondly, fume traces will follow connected flow vectors,

$$fume.Body \supseteq \bigcup_{\substack{ConnectsTo(f',f) \vee \\ ConnectsFrom(f,f')}} f.Body$$

where $f'.Body$ overlaps $fume.Body$. Typically the length of the modelled trace is limited to within some distance from the source object in order to increase the likelihood of an accurate unambiguous sensor reading. □

Using the spatial assistance system, the firefighters can now determine the set of locations from which they should take their sensor readings. If their sensor detects the presence of the fumes at one of these key locations to a sufficiently high degree then the firefighters can follow the modelled fume trace upwind to identify the expected source object. Thus, the firefighters can identify the source of the leak quickly without exhaustively approaching and analysing every potential source object thus minimising the time that they spend in the hazardous environment.

4.2 Spatial Design Assistance for Architects

Architects aim to configure building features such as lighting, object layout, and object materials, in order to evoke complex moods and sometimes even convey deep ideas that reflect an artistic vision. That is, architects must bridge the gap between the objective building design and the highly complex, subjective impressions of the building occupants. This requires architects to routinely analyse and process enormous amounts of detailed numerical information about building features in order to determine whether the appropriate emotions will be conveyed, which can be an extremely tedious, error prone and time consuming exercise.
The primary purpose of spatial assistance applications is to transfer this burden from the user onto the computer system. Automating an architect's ability to reason about subjective concepts requires externalising the spatial awareness capabilities of the architect and formalising this in a spatial assistance system which provides semantic data access services. For example, qualitative concepts such as the apparent brightness of an indoor space are complex and highly subjective; apparent brightness is not only a function of the lumens that are incident on surfaces but also incorporates domain knowledge about the effects of the relative brightness between rooms, the relative brightness of objects in the same room, other properties of objects such as the materials used and so on.

The rules for evoking these subjective responses are rough and qualitative in nature, and ultimately grounded in the geometric relationships and objectively observable features such as lumen measurements, metric wall dimensions and angular orientations. Hence, a multi-perspective spatial assistance system that integrates the numerical, qualitative spatial, and conceptual levels is necessary. Additionally, spatial artefacts are an extremely convenient and versatile mechanism for formalising architectural qualitative concepts. To demonstrate this we will now formalise architectural qualitative domain knowledge and illustrate the utility of our framework through an example design task.

4.2.1 Modelling Architecture Domain Knowledge

The first step is to define an ontology of building objects that architects reason about, and then define their spatial artefacts. This allows architects to specify formal logical expressions that involve all relevant aspects of building objects.

Example 6 (Spatial Artefacts for Light Sources) The range space is the rough, approximate geometry of the beam of light. The functional space is the collection of regions in a room where occupants will benefit from the light source. □

Secondly, we encode the domain knowledge provided by the architectural lighting community. The examples build on each other, starting from the numerical level and working through to the conceptual level.

Definition 2 (Direct Illuminance) The direct illuminance E_d of a surface is the total lumens that travel directly from light sources to the surface (i.e. excluding reflected lumens). Selecting the appropriate light sources simply requires testing whether the range space of the light (i.e. the projected light beam) intersects the surface,

$$surface.E_d = \sum_{\substack{\forall l \in Lights \cdot \\ O(l.Range, surface.Body)}} l.Lumens$$

where O (*overlaps*) is an RCC qualitative relation between regions. □

Definition 3 (First-Bounce Ray Tracing) Determining *lumen incidence* on a surface accurately is, in general, a difficult task that requires sophisticated ray tracing techniques. Cuttle [Cuttle, 2003] provides a first-bounce approximation called the mean surface exitance (Mrs) of a space which takes the surface direct illuminance, area, and reflectance into account,

$$room.Mrs = \frac{\sum_{Contains(room,s)} s.E_d \times s.Area \times s.Reflect}{\sum_{Contains(room,s)} s.Area(1 - s.Reflect)} \quad \square$$

Definition 4 (Surface Illuminance) *The total surface illuminance E is the sum of direct and indirect illuminances,*

$$surface.E = surface.E_d + room.Mrs$$

such that $Contains(room, surface)$. □

Definition 5 (Ambient Illumination) The apparent (qualitative) ambient illumination can be roughly determined as a function of the mean surface exitance. For example, Cuttle [2003] suggests that between approximately $30lm/m^2$ and $100lm/m^2$ corresponds to a dimly lit environment whereas spaces with a mean surface exitance value above $1000lm/m^2$ will appear distinctly bright,

$$AmbientIllumination.Dim(room) = room.Mrs \in [30, 100],$$

$$AmbientIllumination.DistinctlyBright(room) = room.Mrs > 1000 \quad \square$$

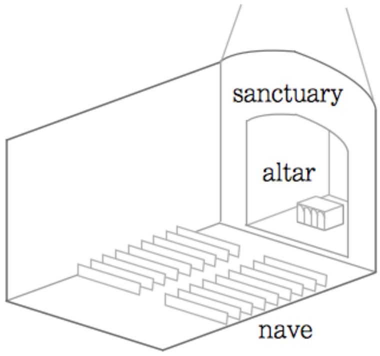

Figure 6: Three key zones of the cathedral interior.

Definition 6 (Perceived Illuminance Difference) The perceived (qualitative) difference in illumination when moving between different rooms and spaces in a building can be roughly determined as a ratio of mean surface exitance values. For example, Cuttle [2003] suggests that a viewer will notice a distinct difference in illumination if the ratio is between 1.5 : 1 to 3 : 1, and the viewer will feel a strong difference when the ratio is between 10 : 1 and 40 : 1,

$$IlluminanceDifference.Distinct(x, y) = \frac{x.Mrs}{y.Mrs} \in [1.5, 3],$$

$$IlluminanceDifference.Strong(x, y) = \frac{x.Mrs}{y.Mrs} \in [10, 40] \quad \square$$

4.2.2 Reasoning for Lighting Intelligence

Having formalised the relevant domain knowledge, the architect is now able to specify instances of designs and employ the semantic data access and reasoning services provided by the spatial assistance system. We now present an example adapted from [Cuttle, 2003].

Example 7 (Illuminating a Cathedral) A lighting designer is required to light the interior of a cathedral, as illustrated in Figure 4.2.2, in preparation for a public concert. The principle aim is to establish a sense of flow through the space and to emphasise the relative focal points of the space by installing and configuring light fixtures. Clearly a uniform lighting distribution is undesirable.

Firstly, the designer establishes that it is the concert attendees who are the primary viewers in whom the lighting designer is aiming to evoke a particular subjective response. As illustrated in Figure 4.2.2 they are located in the nave and must be directed towards the sanctuary which is the clear focal point of space. Within the sanctuary the altar is a particularly significant feature. Thus, within this particular environment there is a hierarchy of focus that creates a flow from the entry, through the nave, towards the sanctuary and culminating at the altar. This hierarchy must be reinforced by the patterns of illumination; the lighting designer can achieve this by creating a hierarchy of qualitatively distinct illuminance differences between the different zones.

It is required that the concert participants in the nave have enough light to be able read the programme during the concert.[9] This visual task establishes a baseline luminance level C required for the nave zone,

$$nave.Mrs = C$$

Next the designer establishes the hierarchy of illumination by specifying their chosen qualitative difference values between the various zones,

$$IlluminanceDifference.Strong(nave, sanctuary),$$
$$IlluminanceDifference.Distinct(sanctuary, altar).$$

[9] Luminance levels required for visual tasks are readily available in recognised lighting codes and standards Rea [2000].

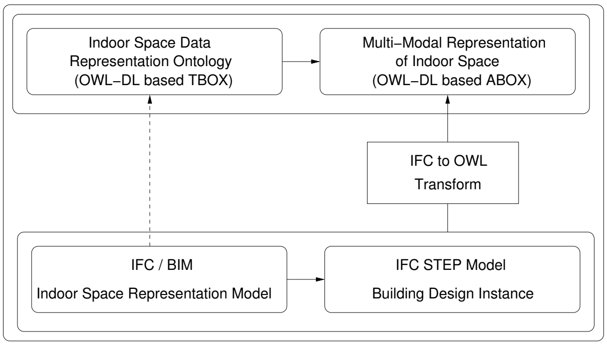

Figure 7: Ontological Grounding – IFC-to-OWL

It is now possible for the reasoner to infer the ranges of qualitative ambient illumination values in all zones, along with other interesting qualitative lighting concepts (such as the overall subjective impression of the space as either hazy, dramatic and so on using research by Flynn et al. [1973], Flynn [1977]). Furthermore, the lighting designer can now freely experiment with different lighting arrangements and get immediate feedback on whether the desired illumination hierarchy has been achieved along with any other information such as the approximate illuminance on any given surface in the cathedral. □

5. CONCLUSION AND OUTLOOK

We have presented a framework for multi-modal spatial data access that is suited to a range of Spatial Assistance Systems. The framework is grounded to industry modelling standards such as IFC and is aimed at facilitating high-level qualitative spatial reasoning abilities. Our framework supports multiple structural forms that provide alternative qualitative characterisations of the building model which are required for particular modes of analysis; for example, route graphs specialise in modelling movement between spaces in a building and thus greatly assist in way-finding tasks. Furthermore, qualitative reasoning often requires the modelling of objects beyond the geometry of the physical body. We have incorporated the notion of spatial artefacts to enable spatial assistance systems to reason about the functional, range and operational aspects of objects. We have demonstrated the versatility of our framework by presenting an emergency rescue case study and an architectural lighting case study. Our future research will focus on the issue of scalability with respect to the effort required to formalise domain knowledge using our framework. Ideally, domain experts (who, in many cases, will have limited experience with logic and formal reasoning) should be able to easily and quickly specify and define qualitative concepts. Furthermore, they must be able to validate their formalisations to ensure that the spatial assistance system is capable of performing the required tasks.

The work described in this paper is a part of a broader initiative for the development of industrially relevant ontological specifications of indoor spatial environments. Figure 7 presents an overview of our framework in relation to IFC. We have developed an extended IFC ontology that also incorporates spatial artefacts and qualitative concepts. This can be used as a schema for defining models that support domain-specific qualitative reasoning, as illustrated in the upper portion of Figure 7; an extract of the schema for modelling walls is illustrated in Figure 4. Work is also in progress to implement the IFC-to-OWL transform illustrated in Fig. 7. Here, the objective is to develop an *Indoor Space Data Representation Ontology* that encompasses industrial data models such as the IFC, and also integrates our perspective toward the representation of the structural form of an environment. Future research will also be geared toward integration with broader standardisation initiatives ([TODO: examples]) within the ISO framework.

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