A DECISION SUPPORT SOFTWARE TOOL FOR REASONING ABOUT THE SUBJECTIVE IMPRESSIONS OF A LIGHTING INSTALLATION

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ABSTRACT

The discipline of architecture is concerned with finding a balance between both the functional and the subjective aspects of a building environment. This involves managing contradictory requirements that are often difficult to resolve through purely numerical analysis; an example of this is an electrical lighting installation designed to evoke a desired subjective impression or ‘atmosphere’, which may conflict with the visual requirements for accurate or safe task performance. Despite this, few software tools exist that directly support an architect when dealing with information relating to the non-visual effects of lighting. A fundamental limitation in standard software tools is the reliance on numerical approaches for representing and reasoning about lighting and construction related information. In particular, when information is uncertain or completely unavailable, numerical formulae can be awkward or impossible to use in a reliable way. Work in the field of qualitative spatial reasoning has attempted to address these issues, and in this paper we present a prototype decision support software tool that reports on the subjective impressions of a lighting scheme, based on a qualitative spatial reasoning engine. Research in subjective response to lighting is reviewed and interpreted in the context of qualitative spatial reasoning, and the prototype system is compared to studies on subjective impressions.

1.0 INTRODUCTION

The discipline of architecture is concerned with more than simply meeting practical criteria, such as: Can the building support the required load? Does the noise level, temperature, or airflow meet the appropriate health and safety standards? Architecture involves the study of how to direct a person’s perception of their environment, for example, to evoke a mood, or to convey an abstract concept. This involves managing possibly contradictory requirements that are often difficult to resolve through purely numerical analysis; an example of this is the subjective impression, or atmosphere of a space that can be evoked by lighting but which may or may not coincide with the visual requirements for safe and effective task performance.

Despite the need to work with the subjective impressions that people experience, few software tools exist that directly support an architect when dealing with information relating to the non-visual effects of lighting. A fundamental limitation in standard software tools is the reliance on numerical approaches for representing and reasoning about lighting and construction related information. For example, the focus of many tools has been on providing computationally expensive simulations such as ray tracing to render or visualise an environment or to calculate luminance distributions across a space (such as (Ward 1994)). One problem is that the level of detail at which processing is being performed is often inappropriate, particularly for early stages of design. Furthermore, when information is uncertain or completely unavailable, numerical formulae can be awkward or impossible to use in a reliable way. For example, a lighting designer may be given preliminary building sketches where materials used and dimensions are only loosely described, and be required to produce a number of different lighting schemes that satisfy subjective and practical requirements.

Other issues relate to usability. For example, computer simulations often result in a large amount of numerical data, involving a variety of units. The architect must then manually determine whether the desired aesthetic and functional requirements are being met, along with health and safety standards. A software tool is required that allows an architect to explore various lighting designs by quickly giving feedback on the non-visual effects of a lighting installation.

Formalisms in the field of qualitative reasoning (a branch of artificial intelligence) have been developed that address the limitations raised by purely numerical systems (Bobrow 1984; Weld and de Kleer 1990; Kuipers 1994; Forbus 1996). The aim of qualitative reasoning is to identify and reason about coarse, qualitatively significant distinctions between object relations. It offers a more human-intuitive approach to working with information by relying on concepts such as causality, the nature of interaction, and by involving everyday terms that capture imprecision and vagueness automatically (such as *very bright*, *fairly dim*, compared to 356 lux). Qualitative spatial reasoning is a subfield that reasons about qualitative distinctions between spatial entities and relationships (Freksa 1991; Cohn and Hazarika 2001).

In this paper we present a qualitative spatial reasoning engine that analyses an electrical lighting installation and reports on the subjective impressions that will be evoked. This prototype system is intended to assist an architect during the early stages of design by providing fast qualitative feedback on the subjective impact of a lighting installation. A framework for capturing qualitative relationships between subjective impressions and physical lighting configurations is presented that allows the compilation of a knowledge base used by the reasoning engine.

2.0 BRIEF REVIEW OF LIGHTING THEORY

In standard lighting theory (Egan 1983; Sanders and McCormick 1993; CIBSE 1994; IESNA 2000; Bridger 2003) luminous flux is a measure of the light energy emitted by a light source, adjusted according to the eye's response to certain wavelengths (for example wavelengths outside of the visible range are excluded). The units for luminous flux are lumens (lm) and can be calculated as:

$$F = P \cdot \eta$$

where P is a light source's power measured in watts and η is the luminous efficacy representing the portion of total radiant flux emitted that is usable for human vision. Illuminance is a quantity for measuring the incident visible light energy (luminous flux) on a surface per unit area, that is, the luminous flux density. The units for illuminance are lux (lx) and for surface s the direct illuminance E_d can be calculated as:

$$E_d = F_s / A_s$$

where F_s is the luminous flux on surface s and A_s is the area of s. Luminous exitance is the density of luminous flux emitted from a surface. The units of luminous exitance are lumens per unit area (lm/m^2) and luminous exitance M_s of surface s can be calculated as:

$$M_s = E_s . \rho_s$$

where E_s is the surface illuminance and ρ_s is the surface reflectance factor which takes a value between 0 and 1. Mean room surface exitance M_{rs} is an approximation of the average illuminance within a room, calculated using the first-bounce lumens, called the first reflected flux (FRF), and the capacity of the surfaces within a room to absorb light, called the room absorption $A\alpha$ (Cuttle 2003) :

$$M_{rs} = FRF / A\alpha$$

For a room with n surfaces, first reflected flux and room absorption can be calculated as the sum of reflected surface flux and the sum of surface absorption respectively (Cuttle 2003) :

$$FRF = \Sigma_{s=1 \text{ to } n} \; E_s(d) . A_s . \rho_s$$

$$A\alpha = \Sigma_{s=1 \text{ to } n} \; A_s (1 - \rho_s)$$

Mean room surface exitance is taken as the average eye illuminance in a room and makes the assumption that the lumens are uniformly distributed. In cases where room illuminance irregularity is an issue, the room can be divided into sections to which the above M_{rs} formula can be applied. A qualitative approach is suggested for scenarios where this is obviously a concern (Cuttle 2003).

The sum of the mean room surface exitance and a surface's direct illuminance component can be used to approximate the surface's total indirect illuminance, E_s (Cuttle 2003) :

$$E_s = E_s(d) + M_{rs}$$

Three categories for describing luminaires are direct, indirect, and diffuse, depending on the amount of light that is emitted above and below the horizontal (Sanders and McCormick 1993). Direct sources emit almost all luminous flux downwards directly illuminating work-surfaces in a person's field of view, indirect sources reversely emit almost all luminous flux upwards which directly illuminates the ceiling rather than work surfaces resulting in more distributed ambient light, and generally, diffuse sources emit equal amounts of light in all directions (Egan 1983).

Correlated Colour temperature (CCT) is a measure of the hue of light, expressed in Kelvins (K), based on the temperature that a theoretical blackbody radiator needs to be raised to emit the most closely matching hue (Cuttle 2003). For example standard incandescent lamps have a CCT between 2700K and 2800K; white fluorescent lamps have a CCT of approximately 3500K.

3.0 BRIEF INTRODUCTION TO QUALITATIVE SPATIAL REASONING

Reasoning about the physical properties of a lighting scheme in a building is used to determine how the light from the luminaires will interact with the objects and surfaces. One numerical approach is simulation where the software system computes the exact distance that a ray of light will travel from a light source before striking a particular surface (e.g. (Ward 1994)). The precise angle of incidence is then calculated, and together this information is used to determine the angle and intensity for the reflected ray. The process is then repeated for a large number of rays, until each ray’s energy is dissipated beyond a threshold. While providing very precise results, such a process is very computationally expensive and requires the characteristics of the surfaces and sources to be provided without ambiguity or uncertainty, and is thus inappropriate in the early stages of an architectural lighting design where detailed information is unavailable. Furthermore vague notions such as *harsh shadows* and the reasoning that uses this type of information (e.g. “crisp harsh shadows can promote tension and drama”) cannot be captured solely by numerical quantities.

On the other hand people use this type of qualitative information to reason about spatial phenomena without resorting to any numerical analysis. This has led to the development of a field called qualitative reasoning (Forbus 1996), which aims at providing methods for reasoning about coarse and uncertain information relating to physical phenomena. More specialised qualitative approaches have focused on reasoning about time, resulting in a subfield called qualitative temporal reasoning, designed to manage coarse-grained causality, action, and change in software systems (e.g. Allen and Koomen’s (1983) action planning application). A notable and highly influential example is Allen’s elegant and efficient interval calculus (Allen 1983), in which a set of thirteen atomic relations between time intervals is defined, a subset of which is shown in Figure 1. A composition table is provided which gives the possible temporal relations between the intervals t_1 and t_3 given relations for (t_1, t_2) and relations for (t_2, t_3), along with an algorithm for reasoning about networks of relations. For example, if:

- A cargo shipment arrives (t_1) *before* the cargo can be inspected (t_2), and
- The cargo is inspected (t_2) *before* the distributors can be contacted (t_3), then
- A cargo shipment (t_1) must also arrive *before* the distributors can be contacted (t_3).

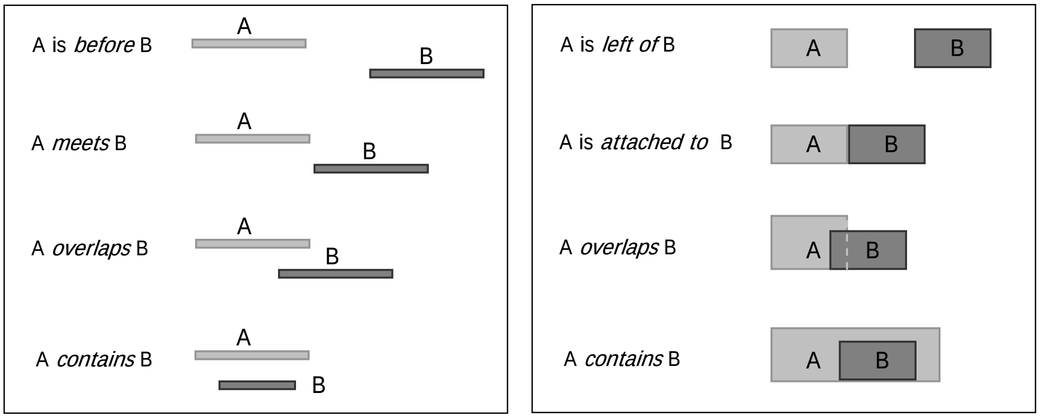


Figure 1: An extract of Allen's (1983) qualitative relations between temporal intervals (left) and an extract of the one-dimensional qualitative spatial relations between two objects presented in Guesgen (1989).

Allen's interval calculus has motivated a number of methods for reasoning about spatial objects and relationships in the area of qualitative spatial reasoning (QSR). In Guesgen (1989) we introduce a cognitively motivated one-dimensional spatial logic directly based on Allen's original temporal logic. The central idea is to represent relative spatial relationships between objects rather than using absolute object positions. Figure 1 illustrates an extract of the basic atomic relationships that are defined.

A transitivity table and constraint satisfaction algorithm are presented for constructing locally consistent networks of spatial relationships. The approach is extended for reasoning about higher dimensions by using an n-tuple of spatial relationships between each pair of objects, where each component of the tuple represents a different dimension of the modeled scene. For example, the three dimensional scene illustrated in Figure 2 can be described with the spatial relations below, if each component of the tuple represents the x, y, and z axes respectively:

O_1 < "inside", "attached to", "inside" > O_2
O_2 < "left of", "inside", "overlapping" > O_3

The possible relationships that can hold between objects O_1 and O_3 are then inferred by applying the transitivity table to the relation components .

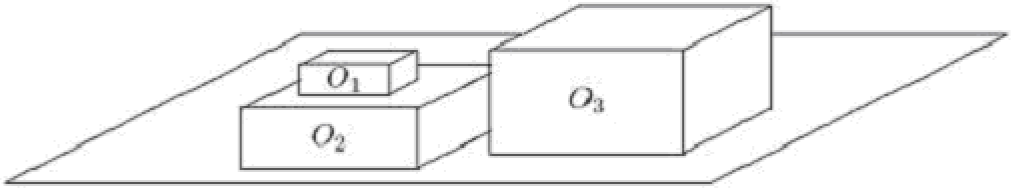


Figure 2: Illustration of a three-dimensional scene of blocks. The relative orientations of the blocks can be expressed in our spatial reasoning method by assessing each dimension independently, and then combining the results (reproduced from Guesgen (1989)).

This method is very appropriate in the context of architecture, as the boundaries of a room are often orthogonally aligned, and surfaces within a room can be approximated by axis-aligned rectangles (the limitations of these surface approximations, in terms of the system's accuracy in determining the subjective impressions of a room, are still being explored).

In the present study, QSR is used to make generalisations about the qualities and behaviour of light and its interaction with surfaces in a room. These lower level qualitative inferences can be combined to reason about intermediate level qualitative characteristics such as *crisp shadows* and *strong flow of light*. High level subjective impressions such as *a spacious, relaxing atmosphere* can be inferred by reasoning about the lower level qualitative measures.

4.0 QUALITATIVE LIGHTING

In this section we review the research on the subjective impressions of electrical lighting schemes and then formalise the qualitative rationale proposed by this research for software automation.

4.1 SUBJECTIVE IMPRESSIONS OF LIGHTING

In the lighting research community it is generally recognised (Sanders and McCormick 1993; CIBSE 1994; IESNA 2000; Bridger 2003) that important factors in lighting an environment include luminance, luminance distribution, uniformity, and spectral power distribution, however a definition of lighting quality is still being debated (Veitch and Newsham 1996). Lighting has both a functional component concerned with the ease and accuracy of visual perception and a subjective component (Jay 2002). It is now clear that a broad range of subjective impressions, such as relaxation, excitement, intimacy, and spaciousness can be achieved by varying aspects of the lighting installation while remaining within the practical health and safety guidelines established according to the task requirements (Cuttle 2003).

Steffy has performed studies on the relationships between luminances, luminous patterns and subjective response (Steffy 2002). The aim was to establish basic guidelines on how to influence a range of non-visual affects with a lighting scheme, resulting in the identification of the following five key impressions (Steffy 2002): (i) visual clarity, referring to a person's subjective impression of how clearly or distinctly interior details, objects, and other people's features appear, ranging from clear to hazy, (ii) spaciousness, referring to the apparent volume of a space, ranging from spacious to cramped, (iii) preference or pleasantness, referring to the subjective evaluation of the lighting environment, ranging from like to dislike, (iv) relaxation, referring to the apparent work intensity, ranging from relaxed to tense, and (v) intimacy, referring to the feeling of privacy in a space, ranging from private to public. The above subjective responses are elicited by a number of intermediate qualitative lighting conditions; these relationships are shown in Table 1. For example, to create a sense of relaxation indirect luminaires could be selectively placed around the periphery (e.g. wall sconces or accent lighting on wall art decorations), complemented with direct low intensity incandescent lamps placed over the area of occupancy (Steffy 2002).

	Clarity	**Spaciousness**	**Relaxation**	**Intimacy**	**Pleasantness**
Ambient Illumination			☑ (bright)	☑ (low in occupancy area)	
Room colour temperature	☑ (cool)		☑ (warm)		☑ (warm)
Perimeter	☑ (some)	☑ (uniform)	☑ (nonuniform)	☑ (high	☑

emphasis				brightness)	
Work surface illumination	☑ (bright, uniform)	☑ (bright, uniform, central)			

Table 1: The lighting conditions (rows) required to elicit the desired subjective impression (columns). Based on research by Steffy (2002) and Flynn (1977), and adapted from (Egan 1983) (pp. 118-119).

Cuttle (2003) proposes six central factors that influence a person's subjective impression of a lighting environment with the aim of supporting architectural design objectives in the creation of a lighting scheme: (i) the ambient illumination in a space, ranging from bright to dim, (ii) the illumination hierarchy that structures a space with varying degrees of emphasis, taking into account the subjective illuminance differences ranging from emphatic to none, (iii) the flow of light through a space, which strongly impacts on the object modelling quality, ranging from dramatic to very weak, (iv) the sharpness of light affecting surface highlights and shadowing, (v) the visible presence of luminous elements, involving glare or sparkle, and (vi) provision for visual performance, defined as the adequate discrimination of colour and detail. We primarily base our work on that of Cuttle and Steffy.

4.2 INTERMEDIATE QUALITATIVE INFERENCES

In this section the qualitative rationale proposed by Cuttle (2003) and Steffy (2002) is formalised in a suitable manner for software automation. The task is to provide an analysis of the subjective reaction that a person will have to a given lighting installation. The interpretation of qualitative lighting concepts such as "bright uniform light across centrally located work surfaces, with some perimeter emphasis" requires the explanation of each qualitative component, for example: What reasoning process is required to determine whether a room has *some* perimeter emphasis? What is the threshold between uniform and non-uniform lighting across a surface? What reasoning process is needed to distinguish between a central and a perimeter surface?

A summary of the different qualitative measures is given in Table 2. Measures 1, 2, 3, 4, 5, and 11 have been selected and derived by the authors, and measures 6, 7, 8, 9, and 10 have been taken from the literature. Each measure is either a property of a model component or a relationship between a pair of components.

Measure	**Type**	**Applicability**	**Values**
1. Source direction	Relation	between source and surface	*at, away*
2.Beam intersection geometry	Relation	between source and surface	*3D shape*
3.Source coverage	Relation	between source and surface	*none, partial, full*
4.Occlusion	Relation	between source and surface	*none, partial, full, n/a*
5.Layout	Property	of sources and surfaces	*central, perimeter*
6.Perceived illuminance difference	Relation	between two illuminances	*none, noticeable, distinct, strong, emphatic*
7.Colour temperature	Property	of sources and rooms	*cool, intermediate, warm*
8.Approx. surface illuminance	Property	of a surface	positive real
9.Illuminance pattern	Property	of surfaces and rooms	*uniform, non-uniform*
10.Ambient illumination	Property	of a room	*none, very dim, dim, acceptably bright, bright, distinctly bright*
11.Perimeter emphasis	Property	of a room	*none, some, lots*

Table 2: Summary of the intermediate qualitative measures used by Cuttle (2003) and Steffy (2002) to infer higher level subjective impressions.

Qualitative source direction is a relationship between a light source and a surface, indicating whether the source is directed towards or away from the surface, based on the geometry and other basic properties of the model.

The qualitative beam intersection shape is an approximation describing the shape of the projected beam on a surface ignoring any occlusion that may occur.

Qualitative source coverage is a relationship between a light source and a surface that indicates whether the projected beam area is significantly smaller than the area of the surface. This is easily determined by considering the qualitative source direction and beam intersection shape.

Qualitative occlusion indicates whether a beam of light is obstructed from striking a surface. It is a relationship between a light source and a surface, and can take the qualitative values of *not occluded*, *possibly occluded* where more information is required, *occluded*, or *not applicable* for cases where the source is not directed towards a surface.

Qualitative layout is a property of sources and surfaces that indicates the region of the room that the component lies in. A qualitative distinction is made between centrally located and perimeter objects by partitioning a room into *central* and *perimeter* volumes.

Perceived illuminance difference is concerned with the amount of variation in illuminance across a space that is needed before a person will perceive a significant change. This can be formalised as a qualitative relationship between two illuminance values indicating the subjective difference that a person will experience. Cuttle informally suggests illuminance ratios required to achieve qualitatively significant categories of perceived illuminance difference, based on exercises conducted with students. These are shown in Table 3.

Perceived difference	Illuminance ratio
Noticeable	1.5:1
Distinct	3:1
Strong	10:1
Emphatic	40:1

Table 3: Illuminance ratios required to achieve the qualitative perceived difference, informally presented in (Cuttle 2003) and based on exercises conducted with students.

The qualitative appearance of different colour temperatures given in Table 4 is widely agreed upon (Egan 1983; Sanders and McCormick 1993; Bridger 2003; Cuttle 2003). Furthermore, studies have been conducted (Steffy 2002) (pp. 59) suggesting that the colour temperature can influence a person's subjective thermal sense according to the qualitative value descriptions. For example, warm light can raise the perceived room temperature by approximately 1.4^{o}C (Steffy 2002). To determine the appearance of a room's colour temperature, a model that combines the colour temperatures of the light sources is required.

Colour appearance	CCT
cool (bluish white)	≥ 5000 K

intermediate (white)	< 5000 K; ≥ 3300 K
warm (yellowish white)	< 3300 K

Table 4: Correlated colour temperatures required to achieve the qualitative, thermally described impression (Cuttle 2003).

The qualitative illuminance pattern distinguishes between *uniform* and *non-uniform* illuminance across a surface and a room. Non-uniform illuminance, for example, can be caused by a localised region on a surface having significantly higher illuminance over other regions. Uniformity can be calculated by taking the ratio between the minimum and average illuminances on a surface and comparing it to a uniformity threshold. For example in CIBSE Code (L05 (3). Lighting Legislation II) (CIBSE 1994) a uniformity threshold is given as 1:1.25.

A numerical approximation for the direct illuminance on a surface has been described in Section 2.0. The flux incident on a surface is the sum of the flux from all sources qualitatively directed *at* the surface that are *not occluded*.

The ambient illumination is the perceived brightness of a space. Research by (Loe, Mansfield et al. 2000) has led to the results presented in Table 5, where threshold illuminance values have been found to satisfactorily correlate with the subjective assessment that people gave for the appearance of a room (Cuttle 2003).

Ambient illumination	Eye Illuminance
Lowest level for reasonable colour discrimination	10 lx
Dim appearance	30 lx
Lowest level for ‘acceptably bright’ appearance	100 lx
Bright appearance	300 lx
Distinctly bright appearance	1000 lx

Table 5: Threshold eye illuminance values for qualitative ambient illumination appearance (Cuttle 2003).

Perimeter emphasis is enhanced by any lighting configuration that provides visual clarity or draws attention to the edges of a room, such as wall wash lighting, accent lighting on art decorations, ornate wall mounted sconces, or well lit side tables. Qualitative perimeter emphasis is a property of a room and can take the values *none*, *some* (perimeter illuminance is approximately equal to central surfaces), or *lots* (perimeter illuminance is significantly greater than central surfaces).

5.0 FRAMEWORK FOR THE APPLICATION OF QSR

We have developed a prototype which applies qualitative spatial reasoning in qualitative lighting design to determine the subjective reaction that an electrical lighting installation will evoke. Figure 3 illustrates the flow of information in the application. The building and lighting installation model is internally represented as surfaces and light sources with various properties such as dimensions, position, and reflectance for surfaces and beam intensity and beam angle for sources. These can be directly taken from a building specification file in a format such as the Industry Foundation Classes (IFC) (Froese, Fischer et al. 1999) model specification. The qualitative relations and properties about model components, as described in the previous section, are then derived by the reasoning engine. The lower level qualitative measures are used to determine the high level subjective impressions of the lighting scheme such as clarity or intimacy. A summary report of the analysis is then produced, specifying the inferred subjective responses along with the rationale behind the reasoning process. Figure 4 illustrates a mockup screenshot of a potential graphical interface for the decision support tool.

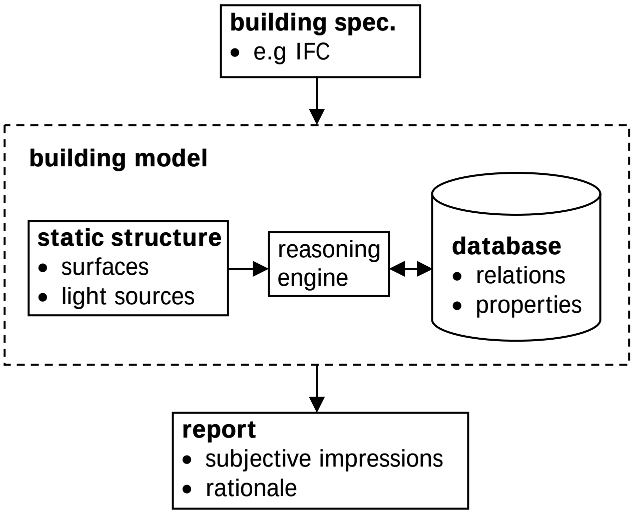
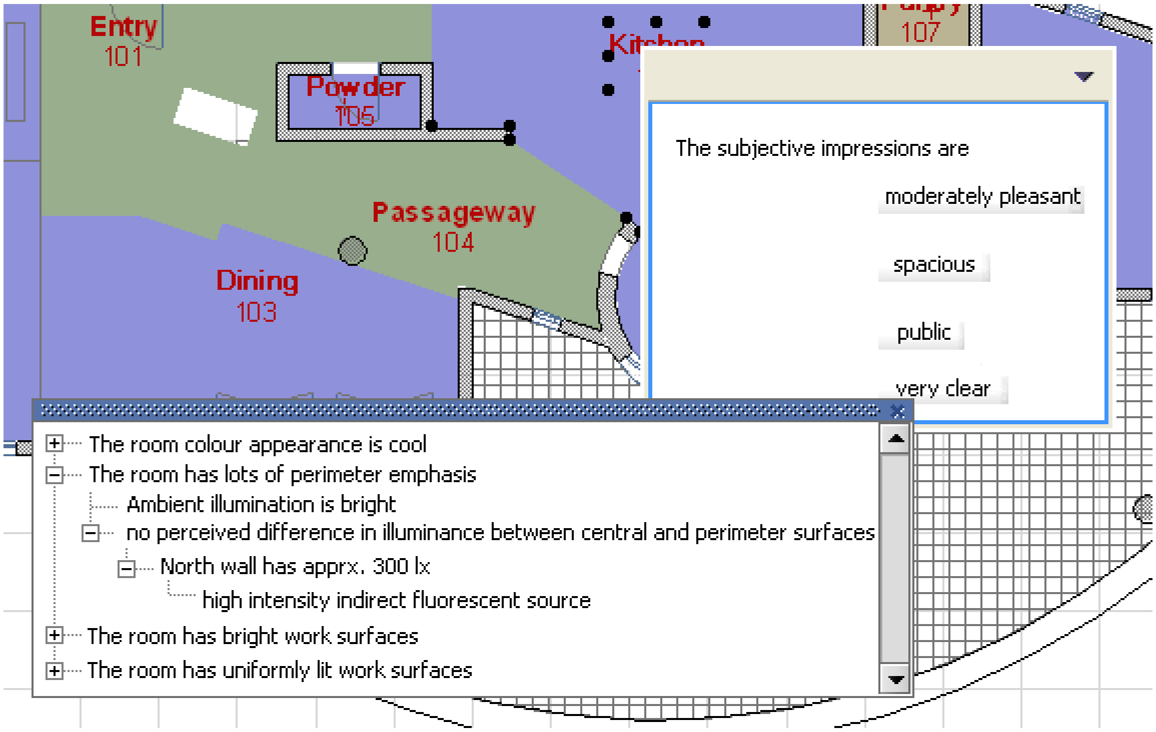


Figure 3: Diagram indicating the flow of information (arrows) between the components (solid and dotted boxes) required to apply QSR to architectural lighting.



The subjective impressions are

moderately pleasant

spacious

public

very clear

- The room colour appearance is cool
- The room has lots of perimeter emphasis
  - Ambient illumination is bright
  - no perceived difference in illuminance between central and perimeter surfaces
    - North wall has apprx. 300 lx
      - high intensity indirect fluorescent source
- The room has bright work surfaces
- The room has uniformly lit work surfaces

Figure 4: Mockup screenshot of a user interface for the subjective impressions analysis engine.

5.2 EXPERIMENTS AND RESULTS

Experiment results conducted by Steffy (2002) (pp. 61-70) have been used to validate the reasoning engine's applicability to lighting design. Steffy presents six different lighting conditions for a meeting room, along with a summary of the qualitative impressions reported by participants of the study. Four different light sources are used in various combinations, which are overhead direct (incandescent), overhead indirect (fluorescent), and peripheral indirect (fluorescent on one wall, incandescent on another). These conditions are presented in Table 6 along with the derived subjective impressions from the QSR reasoning engine.

The reasoning engine correctly determines subjective impressions when strong responses are reported, that is (i) the clarity rating for conditions three, five, and six, (ii) the spaciousness rating for conditions one, two, and six, and (iii) the relaxation rating for conditions three and four. When the response is only moderate the engine still determines the correct qualitative value (e.g. clarity in condition one is generally hazy, which is qualitatively classed as simply *hazy*). When the response is neutral the engine does not respond in a consistent manner between different impressions (e.g. in condition two the neutral clarity rating is assessed as *clear*, whereas in condition three the neutral spaciousness rating is assessed as cramped). The engine requires a further qualitative value *neutral* to capture this intermediate case, or a fuzzy logic approach where membership functions are provided to determine the degree to which a scene is considered *clear* or *hazy*. It must be noted that the results are completely deterministic, that is, identical scenarios will always result in an identical qualitative assessment by the QSR engine. An important future task is to improve the accuracy and robustness of the engine by working closely with experts in the subjective lighting research field. Another future task is to incorporate machine learning techniques where the system will automatically refine the associations between lighting configurations and subjective impressions by analysing a number of examples.

Cond	o/h direct	o/h indirect	p. indirect (fluor.)	p. indirect (incand.)	Study results	QSR engine analysis
1	☑ (low)				Generally hazy, quiet Strong confinement	*hazy,* *cramped*
2			☑ (low)	☑ (low)	Neutral clarity Spacious	*clear,* *spacious*
3		☑ (low)			Strongly hazy, quiet Neutral spaciousness Tense	*hazy,* *cramped* *tense*
4	☑ (low)			☑ (low)	Neutral clarity Mostly neutral spaciousness Relaxed	*hazy,* *cramped,* *relaxed*
5		☑ (high)			Strong clarity Somewhat spacious	*clear,* *spacious*
6	☑ (mod)	☑ (mod)	☑ (mod)	☑ (mod)	Strong clarity Strong spaciousness	*clear,* *spacious*

Table 6: Six lighting conditions used in experiments by Steffy (2002), the qualitative assessments that people gave during the study, and the qualitative assessment given by the prototype QSR reasoning engine.

6.0 CONCLUSIONS

Architectural lighting design requires balancing both functional and subjective requirements. Architectural software tools currently available are not suitable for reasoning about subjectivity, due to the sole reliance on numerical methods for processing information. It is shown here that qualitative spatial reasoning approaches address the key issues raised when using numerical methods, in particular, managing vague and uncertain data, and addressing the usability difficulties of complex numerical tools at an early stage of design. The rationale described by leading researchers in the subjective influence of lighting is formulated in the context of qualitative spatial reasoning in a manner suitable for implementation in software. A prototype system for reasoning about the subjective impressions of an electrical lighting scheme has been presented, and the results of experiments performed by Steffy have been used to validate the approach. The preliminary prototype results are promising and demonstrate the applicability of qualitative spatial reasoning to architectural lighting. Future directions include building more sophisticated and robust qualitative inference functions and incorporating fuzzy logic to allow the system to reason about the degree to which qualitative criteria have been met.

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