Towards a Human-Centered Framework for the Assessment of Subjective Social Values in Buildings

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Abstract

The importance of enhancing the sustainability of buildings has been sharply growing over the last few years. One of the most significant aspects in this regard is social sustainability, as it encompasses the well-being of occupants, how they move through the building, how they perform necessary tasks, and what they experience, e.g., with respect to air quality, visual and thermal comfort, privacy and spaciousness. In this paper, I present my PhD research agenda towards developing a novel framework and logic programming-based analysis tool for automatically analyzing social criteria that are affected by architectural decisions on the spatial arrangement of building elements. The major challenge is that social criteria regulations and design principles are often only specified in qualitative natural language. I present my current progress on developing a systematic approach for formalizing such natural language principles into (first order logic) rules that are applied to digital representations of buildings (Building Information Model, BIM). I present a research plan that includes software prototypes in which I will implement custom constraint logic programming solvers applied to real-world building projects with BIM models, and involving the actual project architect, based in the Aarhus University campus.

Keywords

Building information model, logic programming, architectural qualities, automatic code compliance checking, knowledge representation and reasoning

1. Introduction

The significance of improving the sustainability of buildings has been increasing rapidly over the recent years. While it is important to analyze the environmental aspects in terms of the sustainable performance of the buildings, it is crucial to think of the concept of sustainability in a holistic way, that is, to include social values and subjective qualities.

Such social criteria, like air quality, visual and thermal comfort, curiosity, spaciousness and privacy, play a vital role in promoting the well-being of building occupants, and the lack of these qualities such as not feeling comfortable in a workplace or private in a living room is the cause of having socially unsustainable buildings.

The major issue here is that the design intentions about social values that architects and designers have, are not captured in the Building Information Models BIMs, which is the standard digital representation of buildings [1].

For example, Figure 1 shows a photo of the Aarhus University library as you enter the ground floor. On busy days, the working areas on the ground floor are occupied and students should go

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downstairs to access more work areas. The problem is that the stairwell is dark and students may not know that they can go down. The architect logic in this example is that *"putting a bright light directed at the green wall close to the stairs will increase their curiosity and attract their attention to go down the stairs and explore the working area in the basement"*.
Figures 1 and 2 show the green wall before and after installing the spotlight respectively.

Figure 1: The wall before installing the spotlight

Figure 2: The wall after installing the spotlight

The spotlight will generate a light space, which is the region of empty space that is occupied by the light beam. This light space will be visible to the building occupants within certain range, that is, the light space will generate another special region of empty space which is the visible space, from which the light space is visible. Figures 3 and 4 show the floor plan of the area after generating the light space and the visible space respectively.

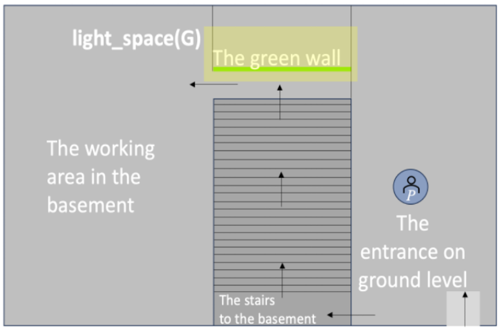

Figure 3: The light space (yellow region)

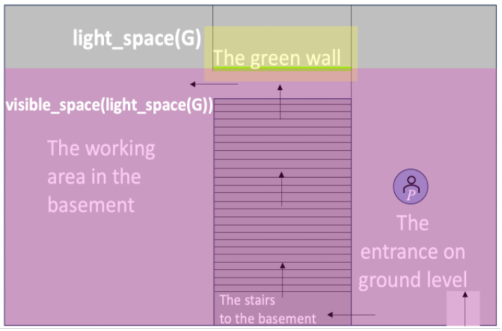

Figure 4: The visible space (purple region)

These regions of empty space are called *spatial artefacts* and will be explained in detail in section 4.3. In order to relate *spatial artefacts* to each other and to other building elements, *spatial prepositions* such as *directed at*, *in front of*, and so on, will be used. *spatial prepositions* will be discussed in detail in section 4.4.

The two main research questions in this work are:

- How to deal with the subjective and qualitative nature of the social value terms, such as curiosity, privacy, etc.
- How to represent the terms of design intentions and social values in a unified knowledge base when they belong to different levels of abstraction, such as visible space, bright, spotlight, etc.

The term *social value* refers to any aspect that affects the well-being of building occupants, e.g. sense of privacy, spaciousness, belonging etc. Most of these terms that are related to human-centered qualities are ambiguous and can tolerate a wide range of interpretation possibilities, that is, they are not straight forward to evaluate as they can differ according to many different factors like location, environment, the function of the building, etc.

The challenge is how to formalize such a wide range and broad scope of values when they are subjective, vary from one environment to another and some of them might be contradictory.

Moreover, terms like walls, doors and slabs represent building elements, while spaciousness, privacy and curiosity are all social qualities that represent the behavioral experience of the building occupants, the challenge is to represent them in one knowledge base by creating a network of social values and design intentions related through *spatial prepositions*.

To address the mentioned research questions, the following contributions are presented:

- The 3-level formalization approach (the goal level, the domain level and the product level) is introduced.
- Formalization of architects' design intentions, decisions and reasoning regarding human experience in the form of first order logic formulas.

The next step is to show how these formulas can be interpreted and verified on a BIM model through some computational procedure, in order to be tracked and maintained by storing these intermediate calculations and using the concept of *spatial artefacts*, like *light space*, *visibility space*, which are a generated from different building elements.

In my PhD project, I am developing a new framework (in the context of knowledge representation and reasoning) that allows architects to:

- Formally capture *design intentions* about *social values*.
- Define the computational procedures for evaluating *spatial prepositions* and for computing the geometry of *spatial artefacts* as components of these formal design intentions, this includes generating the *spatial artefacts* of certain objects based on their specifications such as their size, dimensions, orientation etc. In addition, the interpretations of the predicates will also be included in the design intention objects.

Lastly, the interpretations will later be used to reproduce the results when it is time to rerun the algorithm and recalculate the formulas for further checking procedures. For example, architects and other members of the design team should be able to rerun the proposed algorithm after making different changes on the design. They should get a new report with the effects of

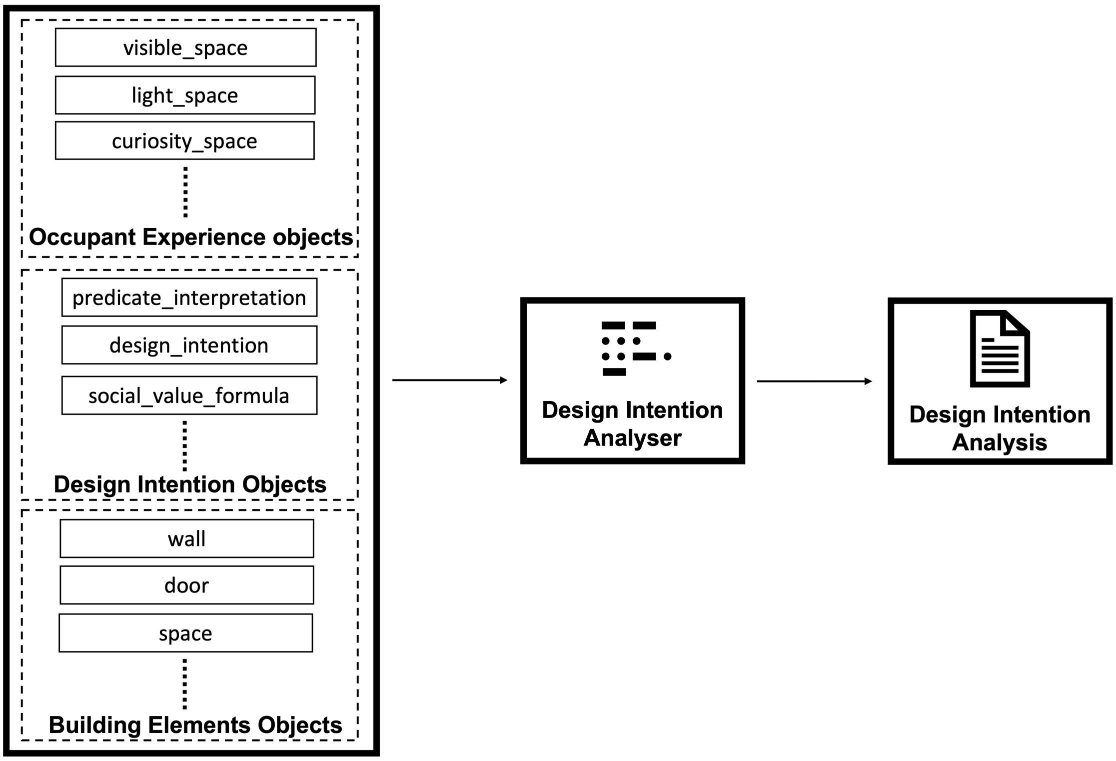

Figure 5: A block diagram of the overall system

those changes on the satisfaction of different design intentions. In the library example, the original design might have that bright spotlight directed at the wall with the design intention of creating a sense of curiosity. Energy engineers might change the design by removing that bright spotlight to save energy. When the algorithm is rerun, they will get a notification in the new report that the original design intention has been violated, and that the social value (the sense of curiosity) has been affected. Figure 5 shows a block diagram of the overall system.

2. Related work

The main research activities in this PhD project primarily draw from advances in *Knowledge Representation and Reasoning*, *Constraint Logic Programming* as well as *Formalization* and *Automatic Code Compliance Checking*.

There have been a lot of efforts in the field of standards formalization. The authors in [2] for example present the ”LegalRuleML” standard, which represents an extension of the ”RuleML” to formalise legal documents by converting rules that are presented in natural language to machine language for automatic analysis. Another concept introduced by [3] is the ”RASE”, which stands for requirement, applicabilities, selection and exceptions of texts for automatic generation of logical statements.

Building code compliance checking that is based on Computer-Aided Design (CAD) tools is time consuming and costly process and needs a lot of human effort [4]. A lot of research has been conducted in the area of automated building codes compliance checking, which refers to the process of computer-based reviewing of the drawings and specification regulations which helps reducing time and cost of manual procedures and provide a better review quality[5]. The authors in [6] presented an examination of rule-based checking systems of building designs.

The work that is presented in my paper falls into the category of rule-based checking as it directly relates to the approach of having rules interpretation, which means translating the rules from natural language to computer language, then rule execution, which is performed on building models that are based on IFC standard and finally providing the results of the checking process.

The researchers in [7] summarise the research activity that has been going on for the last years in the area of automation of code compliance checking.

Some examples include the ”STEEL-3D”, a graphical CAD system that was mainly developed for the design of steel frames. Another example is the Standards Interface for Computer Aided Design (SICAD), which goal was to extract information from the standards. After the emerging of artificial intelligence a new expert system called ”BUILD” was developed.

The authors mention the effect of introducing the prominent open BIM standard known as Industry Foundation Classes (IFC) on the development of the current tools such as the Express Data Manager (EDM), the Solibri Model Checker (SMC) and Design Data System (DDS) etc.

The researchers in [7] also identify a research gap in the area of performance-based and subjective qualitative values. Such performance-based criteria can directly affect the well-being of building users, and consequently affect the social sustainability of the building which is one of the pillars of the general sustainability concept. However, the main difference between social sustainability and the other pillars, i.e. economic and environmental sustainability is the lack of one clear definition, as a result it is considered to have a collection of terms under it and all these terms are ultimately directed towards how people feel [8].

Those terms that are used to describe and assess social sustainability in the built environment are the ones that directly affect the well-being and comfort of building occupants. For example, sense of privacy, safety, community, quality of life in terms of satisfying certain thermal, visual, acoustic standards, etc. These factors of social sustainability can be affected by manipulating building elements including walls, windows, artificial lighting, etc.

The authors in [9] define four spatial quality determinants to be used in the assessment of spatial quality in building renovation. These determinants are:
1- View: from the inside to the outside and from the outside to the inside, i.e. the visual privacy.
2- Internal spatial arrangements: internal division of space.
3- Transition between public and private spaces.
4- Perceived built human densities: population density and different functions of spaces.

Relevant to the sense of privacy, the authors in [10] define the privacy parameter of a point in a specific area observed from external spaces as well as the visual openness parameter. The two parameters are related as the visual openness affects the sense of privacy in the building.

Another example is the work of [11], the authors show how design variations (such as the form of windows) affect the size impression of a room. For example, vertical windows make the room appear higher while horizontal windows make it appear wider.

3. Methodology

In order to represent the architecture quality principles in this work, I follow the IDEF5 process for ontology capture (organising and scoping, data collection, data analysis, initial ontology development, refinement and validation). I am developing the human centered framework in an incremental iterative way based on a case study driven approach.

The case studies represent actual projects taking place at Aarhus University. All of these case studies target the Danish architects context. In the first phase, I am developing the framework using five real renovation projects, they are based in Aarhus University and they are part of campus 2.0[1]. Some examples of these projects include the Molecular Biology Building, the Nobel Park Library, Centre for Educational Development (CED), the Kitchen 2.0, and the School of Business and Social Sciences (BSS). As a special case we are going to focus on the Kitchen 2.0 and do in-detail air quality related analysis.

I am also in direct interactions with the project's key architect (Gustaf Lohm) who is responsible for the renovation works. At the initial phase of the project, I also took some design intentions from the work of Kristoffersen [8] where she presented different scenarios of design decisions in her master thesis.

Figure 6: Top view visualisation of the University City. Credit: AART Architects

The aim is to formally and comprehensively represent *every* design intention argument that architect Lohm comes up with, and to introduce a detailed formalization of real-world design intentions. This encompasses a wide range of situations, sense modalities, and social values, so that the framework develops to be suitably expressive, and I plan to engage with broader range

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[1] https://international.au.dk/about/profile/campus-20

of architects in the future. Given the connection with architect Lohm, I either have the BIM models or the detailed floor plans from which the BIM models will be prepared.

During the formalization process, I have discussions with architect Lohm to get the updated design intentions and the decisions they make, in addition to site visits to the actual buildings to take photos and get a closer look on the implementations of their ideas.

In the first phase, I extend the Industry Foundation Classes (IFC) as a BIM standard used to capture design intentions in a formal way. In addition, I implement a simple solver written in Python using standard algorithms. The purpose of this solver is to check whether a certain formula is true or not for a given BIM model. This prototype will also allow to explore the problem and identify any issues in terms of run-time performance. For example if we have a large number of formulas or a large number of BIM objects, how long does it take to run the algorithm. The prototype will help in experimenting what types of reasoning services are important, for example, which formulas are possibly affected by changing a certain BIM object. The solver will be applied to BIM models of real-world building projects, and involving the actual project architect, based in the Aarhus University campus. Once I have a clear list of reasoning tasks and benchmark tests, I plan to look at some existing specialized solvers. Figure 7 shows the timeline of my PhD plan.

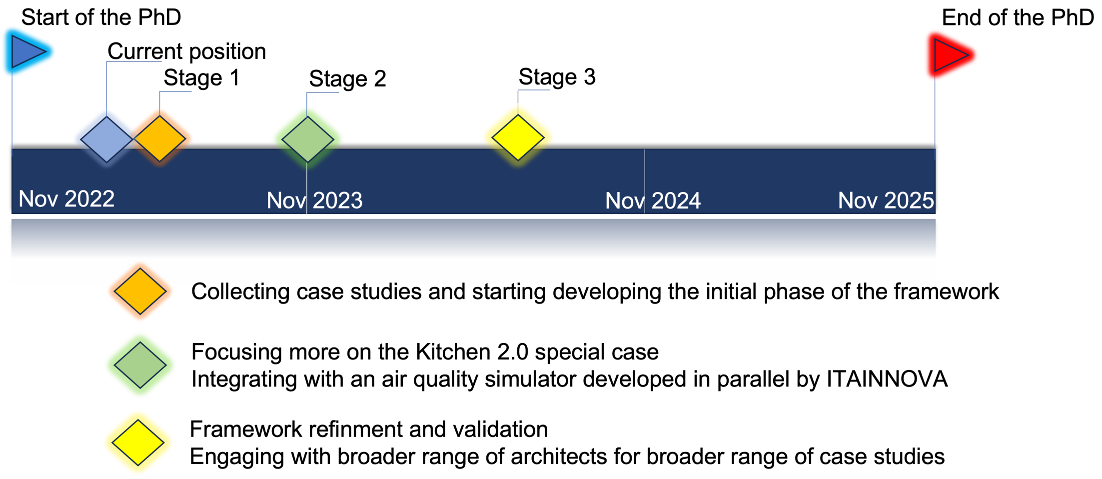

Figure 7: Timeline of my PhD plan

One limitation of this work is using Danish cases as the data source to create the framework, this decision may generate some bias towards the Danish design and building standards.

4. Overview of the human-centered framework

One major idea of this approach is to capture social values in what I refer to as a *bottom-up* rather than in a *top-down* way. Considering the “view” determinant in [9] as an example to illustrate the approach of the proposed framework, a *top-down* approach of formalization means that the concept of ”privacy”, must be universally defined using a set of rules. However, a *bottom-up* formalization would give the architects the ability to define the term *"privacy"* based on their application domain.

It would be the same if we consider the library example, a *top-down* approach would mean that a social quality, such as *"curiosity"*, is defined in a universal, project-independent way by hard-coding a set of rules. However, *"curiosity"* is a subjective and qualitative term and does not have a universal definition.

A *bottom-up* approach means that there is no formalization of the term *"curiosity"* using universal rules, instead, we enable architects to put together their design intention arguments by providing them with a domain-specific language and a standard structured argument form so that they can create their own project specific definition. This approach will not provide hard coded definitions but a toolbox, which the architects can use to build their own rules given the form and the structure that they have to follow. This will guarantee the flexibility to organize their thoughts by capturing the way they are thinking.

The proposed domain specific language is represented in this structured setup, with the help of *the 3-level model*, in addition to the new object types of *spatial artefacts* and *spatial preposition predicates*, which are presented in detail in the following sections.

4.1. A formal argument structure for architects' logic

In the human-centered framework, I adapt the four requirement levels of Lauesen [12] in "requirements engineering" to introduce the three human-centered formula levels. Each level corresponds to a first-order formula [13]. This approach is used to formalize design intentions, as a first attempt at providing some structure for an architect's argumentation on as-designed social values.

The first level of the model is the *goal level*, which represents the ultimate focus and the main influence on the building occupants. This level describes the social value that is under consideration, which is the sense of curiosity in the library example. Assuming that P is a building occupant, R is a room in that building, and "sense_of_curiosity" is the goal predicate. A building occupant P has a sense of curiosity about room R represents the goal level. The formula of this level can be expressed as:

goal: sense_of_curiosity(P,R)

The second level is the *domain level*, this level represents the underlying logic connecting the goal level to the users. It is very important to note that this level does not describe how the goal level is going to be achieved in terms of design and building elements. So in the library example, there is no information at this level about the source of light, it's dimensions, coordinates or luminous value. Using the spatial predicate *"inside"* and assuming that G is a spotlight that generates a *light space*, then the user P must be *"inside"* the *visible space* of that *light space* to achieve the goal of increasing their sense of curiosity in the room. The domain level formula can be expressed as:

domain: inside(P,visible_space(light_space(G)))

The third level is the *product level*, this level explicitly describes how the domain level influence is achieved in terms of design and building element decisions. In the library example, one way to achieve the influence of increasing the sense of curiosity is to have a bright spotlight directed at the wall. Assuming that G is a building element of type spotlight and it is bright, W is a building element of type wall, and G is *directed at* W, the product level formula can be expressed as:

$$\textit{product: } \textit{type}(\textit{spotlight},G) \wedge \textit{bright}(G) \wedge \textit{type}(\textit{wall},W) \wedge \textit{directed\_at}(G,W)$$

4.2. Characterizing the logical nature of architects' argument

In this framework the goal is to link structured architecture arguments to a more formal logical system. The logical system is not deductive in nature, as some domain arguments might even give contradictory goal levels.

For example, one can argue that adding a private outdoor space like a balcony, a terrace or a backyard to a building will increase the sense of privacy of the building as it creates a buffer zone, by increasing the distance between the private and the public area and pushing the movement space of people outside further away from the private areas.

A contradictory argument is that adding a balcony or any other opening will increase the exposure of the inside to the outside and hence increasing the chances of being seen or observed through that addition and as a result decreasing the sense of privacy.

Figure 8 demonstrates the example of contradictory arguments and how it is related to the three-level model proposed in this framework. One branch of the domain level will have more visibility from the outside to the inside and as a result decreasing the level of privacy and the other branch will show that the movement space is pushed away creating a buffer zone so that the outside observer is further away from the private area and as a result increasing the sense of privacy.

Therefore, I am reviewing other logical systems as a potential foundation for design intention arguments, such as paraconsistent logic [14], relevant logic[15] and default logic [16].

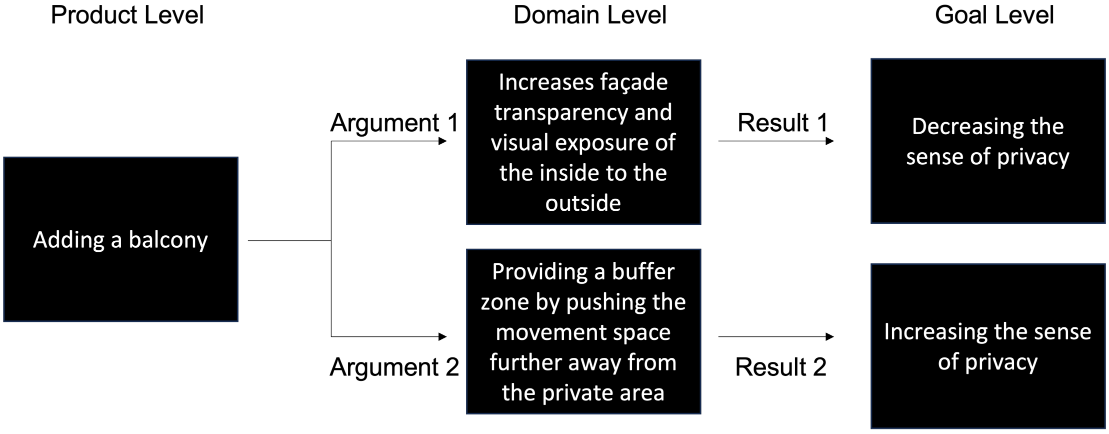

Figure 8: Contradictory arguments example

One additional layer of reasoning that I would like to develop in later stages of the work is the ability of the framework to reason about arguments that might represent violation of common sense. This idea is inspired by the work of [17].

The approach described in Section 4.1 so far does not formally relate the predicates in the domain level to the goal level. The result is that the architect can claim *any* goal level experience, including clear violations in common-sense, and my framework will not be able to detect any issues.

Thus, my framework will enable architects to assign goal level predicates (such as *privacy*) with underlying principles, also in the form of formulas. For example, an underlying principle for eliciting the sense of privacy is that the occupant, *O* should not feel exposed to other people in the environment, *P*:

not(exposed(O,P))

We can then link domain level concepts (e.g. visibility) with such underlying principles, e.g.

visible(O,P) -> exposed(O,P)
audible(O,P) -> exposed(O,P)

and so on.

In this way, common sense inferences can determine whether the domain level formulas really support the goal level, via these underlying principles.

4.3. Spatial artefact

This section introduces the concept of *spatial artefact* [18], [19] and how it is going to be implemented throughout the development of the proposed framework. A spatial artefact is a region of empty space that represents the area in which an object can be seen, heard, used, etc., that is, regions where occupants have a particular experience, or behave in a certain way. In the library example mentioned earlier, consider the region of space that is occupied by the light beam generated by the spotlight that is directed at the wall, this space is very informative and crucial to determine where the users must stand to see that light.

This space represents a *spatial artefact*, that is, a *light space*. The geometry and dimensions of this *light space* depend on the light source itself and the surrounding objects e.g., walls, stairs, windows and any other obstacles.

For the building occupants to be able to see the *light space*, they must be within certain region determined by that *light space*, this region is called the *visible space*. The building occupants will see the *light space* if they are located inside the *visible space* of that *light space*. The *visible space* of the *light space* can also be called the *curiosity space* as it is the region of space where building occupants should have a sense of curiosity as they can see the light space when they are located inside this region.

Other examples of such spaces (*spatial artefacts*) include the *movement space* of a room where people can move within a room surrounded by different objects like walls, doors and furniture. Another example is the *visibility space* or the *hearing space* of humans, which define the region of empty space where humans can see or hear the visual or acoustic experience produced by a certain object respectively.

These examples of *spatial artefacts*, where regions of empty space are meaningful and contain a very important semantic value of experience and design intentions, will be integrated into the building model just as any other building objects, the key difference that they have compared to ordinary building elements is that they get their own characteristics i.e. shapes, geometries and dimensions from the sources that they generate them and the objects that they are surrounded by.

Figures 9 and 10 show a demonstration of the *light space* and the *visible space* of the *light space* respectively.

Figure 9: The light space - a spatial artefact

Figure 10: The visible space - a spatial artefact

4.4. Spatial prepositions

Spatial prepositions refer to terms like *in front of*, *between*, *near*, *inside*, *directed at* etc. They are responsible for representing the direction, orientation, or position information of spatial artefacts and building elements. It is important to keep these terms in the structured arguments because they capture the intention of the architects in an elegant way. However they also suffer from the same problem of the goal level terms, that is, they are subjective and very much case specific.

In the library example, the *"directed at"* spatial preposition has been used. In a *top-down* approach this means that a universal definition of the light being directed at or facing an object will be hard coded. Instead, using the *bottom-up* approach means developing a domain specific language for defining *spatial prepositions*. This aspect is informed by the research in the area of *spatial qualitative reasoning* such as connection calculus [20].

These *spatial prepositions* are categorized or broken down according to how they make constraints on the objects involved, if architects are allowed to choose then they specify the most suitable sufficient criteria. Some examples of such constrains include position, size, shape and orientation.

For example, an architect suggested that putting a tree outside in front of the window will increase the sense of privacy of the building occupant by reducing the amount of exposure of the inside to the outside. Assuming that the orientation and the position of the window are fixed, and the position of the tree is variable, the ”in front” preposition means a region of space where the tree can be positioned, this means that it is a positional constraint on the tree and the architect can decide where that ”in front” region is.

In the opposite case, where the tree is fixed and the window has both position and orientation constraints, the ”in front” region is defined by both the position and the orientation constraints.

Another predicate could be ”far”, it is also a positional constraint but the difference is that the region that it generates can not touch the window because it does not make sense for an object to be considered far from another object while it is already touching it. In the case of ”far” predicate, the generated region would look like a doughnut-shape with the window in the middle.

5. Integrating human-centered framework into BIM standards

The proposed framework will take the existing BIM standard, which is the Industry Foundation Classes (IFC) in this case. This standard contains classes of ordinary building elements like (IfcWall) which is a subclass of the building elements class (IfcBuildingElement) and extend it with classes that represent occupant experience and behaviors as regions of empty space like the *visible space* in the library example.

A new class dedicated for the spatial artefacts is (IfcSpatialArtefact) that is a subclass of the (IfcSpatialZone) class. Subclass of the spatial artefact class include the functional space (IfcFunctionalSpace) and the operational space (IfcOperationalSpace) and so on. Another subclass is the range space (IfcRangeSpace) which also include other subclasses representing the range of experience of humans, for example, the visibility space (IfcVisibilitySpace) and the hearing space (IfcHearingSpace).

In addition, a new class for the social value concept is created as a subclass of the (IfcObject) class, and this subclass will include other subclasses to represent design intentions and the architect’s definition of the qualitative predicates. Figures 11 and 12 show occupant experience and behaviour classes as a refinement of IfcSpatialZone and social value concepts as a subclass of the IfcObject class.

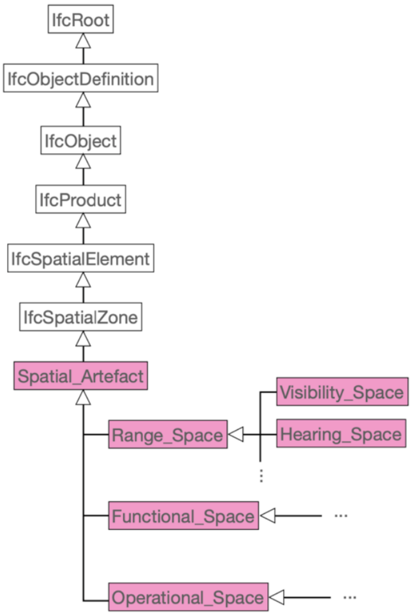

Figure 11: Occupant experience classes

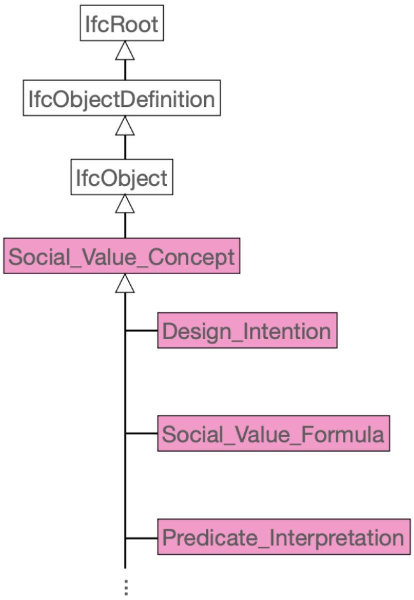

Figure 12: Social value concepts

6. Conclusions

The aim of this research is to develop a human-centered framework that will allow architects to capture design intentions about social values in buildings in a formal way and integrate them into Building Information Models (BIMs).

The research questions are how to deal with the qualitative and subjective nature of the social value terms, and how to represent terms and concepts that belong to different levels of abstraction in a unified knowledge base.

The main contributions of my research are adapting the three-level formalization model (the goal level, the domain level and the product level) and to formalize architects' design intentions and reasoning as first order logic formulas. These formulas will later be interpreted and checked on the BIM models.

This work follows a case study driven approach, in which real case studies of buildings of Aarhus University campus are used for formalization procedures as well as direct communication with key architects, who are working on the projects, via meetings and site visits.

Currently I am working on a case study that is the Molecular Biology Building of Aarhus University, where I am trying to formalize the design intentions of the architect responsible for the renovation and refurbishment works in the building.

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References

[1] K.-d. Wong, Q. Fan, Building information modelling (bim) for sustainable building design, Facilities 31 (2013) 138–157.
[2] P. Ghannad, Y.-C. Lee, J. Dimyadi, W. Solihin, Modularized bim data validation framework integrating visual programming language with legalruleml, in: Advances in Informatics and Computing in Civil and Construction Engineering: Proceedings of the 35th CIB W78 2018 Conference: IT in Design, Construction, and Management, Springer, 2018, pp. 85–93.
[3] E. Hjelseth, N. Nisbet, Capturing normative constraints by use of the semantic mark-up rase methodology, in: Proceedings of CIB W78-W102 Conference, 2011, pp. 1–10.
[4] T.-H. Nguyen, J.-L. Kim, Building code compliance checking using bim technology, in: Proceedings of the 2011 winter simulation conference (WSC), IEEE, 2011, pp. 3395–3400.
[5] J. Peng, X. Liu, Automated code compliance checking research based on bim and knowledge graph, Scientific Reports 13 (2023) 7065.
[6] C. Eastman, J.-m. Lee, Y.-s. Jeong, J.-k. Lee, Automatic rule-based checking of building designs, Automation in construction 18 (2009) 1011–1033.
[7] J. Dimyadi, R. Amor, Automated building code compliance checking–where is it at, Proceedings of CIB WBC 6 (2013).
[8] A. E. Kristoffersen, Social sustainability of buildings a comparison of social qualities in building certification systems, and the development of a catalogue for quantitatively assessing and communicating environmental-, economic-, and social impacts of social intents. master's thesis, department of civil and architectural engineering, (2023).
[9] F. Acre, A. Wyckmans, Spatial quality determinants for residential building renovation: A methodological approach to the development of spatial quality assessment, International Journal of Sustainable Building Technology and Urban Development 5 (2014) 183–204.
[10] A. Indraprastha, M. Shinozaki, Computational models for measuring spatial quality of interior design in virtual environment, Building and Environment 49 (2012) 67–85.
[11] B. Matusiak, The impact of window form on the size impression of the room—full-scale studies, Architectural Science Review 49 (2006) 43–51.
[12] S. Lauesen, Software requirements: styles and techniques, Pearson Education, 2002.
[13] C. Schultz, Y. N. Zayed, A. E. Kristoffersen, G. Lohm, A. Kamari, Towards a human-centred framework for representing and reasoning about social values in buildings, The 30th EG-ICE: International Conference on Intelligent Computing in Engineering, University College London, London, UK (2023).
[14] J. M. Abe, S. Akama, K. Nakamatsu, Introduction to annotated logics: foundations for paracomplete and paraconsistent reasoning, volume 88, Springer, 2015.

[15] A. Urquhart, Semantics for relevant logics, The Journal of Symbolic Logic 37 (1972) 159–169.

[16] P. J. Hayes, The logic of frames, in: Readings in artificial intelligence, Elsevier, 1981, pp. 451–458.

[17] E. Davis, Naive physics perplex, AI magazine 19 (1998) 51–51.

[18] M. Bhatt, C. Schultz, M. Huang, The shape of empty space: Human-centred cognitive foundations in computing for spatial design, in: 2012 IEEE symposium on visual languages and human-centric computing (VL/HCC), IEEE, 2012, pp. 33–40.

[19] M. Bhatt, J. Hois, O. Kutz, F. Dylla, Modelling functional requirements in spatial design, in: Conceptual Modeling–ER 2010: 29th International Conference on Conceptual Modeling, Vancouver, BC, Canada, November 1-4, 2010. Proceedings 29, Springer, 2010, pp. 464–470.

[20] A. G. Cohn, B. Bennett, J. Gooday, N. M. Gotts, Qualitative spatial representation and reasoning with the region connection calculus, geoinformatica 1 (1997) 275–316.