A Context-Knowledge Model for Architectural Design

A holistic approach by means of artificial intelligence techniques

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Abstract. *From the earliest stages of the Architectural Design Process, designers have to take a lot of design decisions mostly based on "Context". The present research is aimed at developing a Context Knowledge Model to improve the representation of 'Context' for architectural design. 'Context' has been analysed and formalized by means of Ontologies related to the entities most frequently involved in architectural design, namely environmental, social, economic and normative entities.*
The development of such a model to manage 'Context' parameters can improve the knowledge of 'Context' of designers involved in a design project in order to advise them of how it affects their design solutions. Moreover, Artificial Intelligence techniques have been explored to improve its performance.
Keywords. *Architectural design; holistic context; knowledge representation; early-stage design; AI techniques.*

A HOLISTIC APPROACH TO CONTEXT

During architectural design process, the definition of building is related to a large amount of context knowledge. 'Context' is understood in this paper in a holistic sense as knowledge containing information about surrounding physical and cultural factors and interactions having an impact on the design and the behaviour of the architectural design at a particular moment in time (Rehman and Yan, 2008).

While much has been done in the architectural design process regarding design 'Product' (the building project) representation, in spite of architectural databases and knowledge (Eastman, 1999; Carrara et al., 2009; etc.), 'Context' is a still a knowledge area that is not fully represented and implemented in a holistic way during the design process despite its relevance.

Context has always been important in architectural design, but new design needs, such as sustainability, free forms, relationship with the district, urban transportation and innovative construction technologies have revealed the need for a new approach to implementing and managing this kind of 'knowledge'.

Currently, Context is also used in Google Earth in a simple form to represent streets, coordinates, advertisements, shops, etc., it but lacks reasoning, knowledge, cultural aspects, urban tissue density and urban codes integrated with other knowledge domains, such as knowledge of procedures or actors' knowledge in order to be effectively useful.

Moreover, the design process having an operational scope requires the designer to have the ability to relate to the 'context' and the architectural 'product' in increasing complexity.

At the same time, a number of Context Knowledge modelling studies (Gursel et al., 2009) have shown how a digital/computational representation of context would allow them to interface with current application programs, so that designers can coherently check and improve the building's performance, themselves affecting or being affected by the context and becoming more aware of the impact of their decisions regarding the overall project right from the early design stages.

In order to provide a representation model able to implement 'Context' knowledge, it was decided to rely on architectural design knowledge representation that has already been developed, presented and discussed among the scientific community by this research group (Fioravanti et al., 2011), and to actually extend it from the product to the context knowledge areas. Underlying the model proposed in this paper is an ontology-based representation that allows different context entities to be formalized and structured homogenously, and to be linked with 'Product' entities; that is, it is strictly part of the designed product and can be divided in two Macro-Classes: Physical Elements and Spaces. The first set includes all the components of the building and the product in general, while the second one includes all the spaces bounded by or containing other components, products and spaces. The result is a comprehensive model where the relations between context and building are explicit, integrated and accessible to designers to support their decisions during the design process, also exploring Artificial Intelligence techniques to improve the efficiency of the model.

RATIONALE/STATE OF ART OF 'CONTEXT'

Context has an important role from the early stages of design as it influences all phases of the Design Process. It can be perceived in different ways, for example, in relation to the place, as physical and tangible, place structure, cultural and conceptual context, in relation to technologies and their use, etc.

Context in Architectural Design is usually represented, analysed and, most generally, taken into account by means of different approaches such as:

- *Geometry* based on graphic editors, orography, dimension of surrounding buildings, road network, e.g. historical evolution and institutional management in a GIS /DB (Apollonio et al., 2010), by means of structured geometry and documentary from multiple sources for the purpose of enhancing knowledge of these sites;
- *Evaluation* based on SBM (Single Building Modeling) paradigm software in which information is organized around the construction data, natural, social or building use e.g. dynamic design aspects (e.g. wind, pedestrian flow, functional usage) (Wurzer et al., 2012) using Agent Based Simulation in the early planning stages to analyse the context;
- *Generative* systems organized on a program of data representing the main architectural spaces, selecting and conceptualizing some elements of context, e.g. to employ generative methods at an early stage of architectural design to take terrain and sunlight into consideration (Li and Li, 2011) ;
- *Evolutionary* and *Knowledge* based technology systems that analyse context ontology for different purposes, e.g. a Service Oriented Context Aware Middleware (SOCAM) architecture for building on context aware services (Gu et al., 2004) or to assist in the management of multiple external ontologies of building components in support of an information model designed for lifecycle building performance assessment activities (Gursel et al., 2009).

The latter approach is the one most closely related to the research approach because it can be implemented in order to obtain a holistic concept of context for Architectural Design. The main benefit of this approach is the ability to take into account various contexts and to have the possibility of linking these aspects to other different aspects.

Our Context Knowledge Model is one of the 'realms' of the 'Tetrahedron of Knowledge', a graphi-

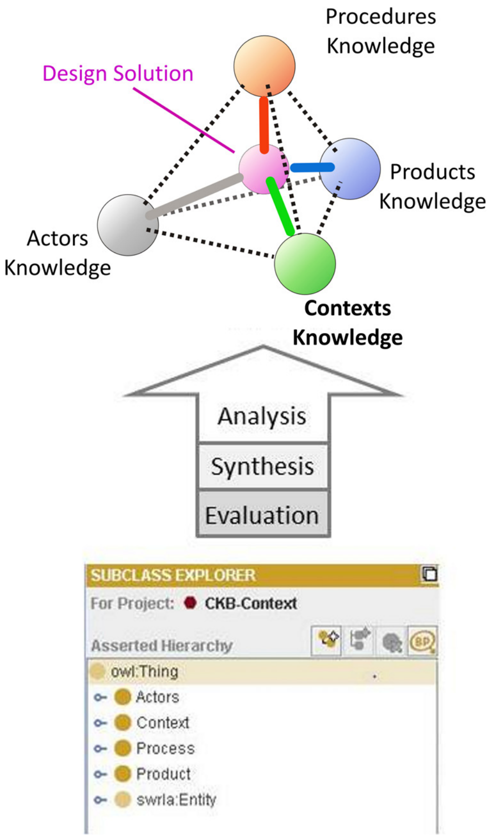


Figure 1
Context Knowledge in the tetrahedron of Knowledge Realms.

cal representation of the main domains related to the development of the design solution in architectural design (Fioravanti et al., 2011), through the analysis, synthesis and evaluation of different possibilities (Figure1).

This Realm has been defined and populated by codes, design experience, climate data, laws of physics, etc. In the design process it is very useful for analyzing the site in the early stages of design through evaluation, warnings and advice to help actors to attain the synthesis of design.

The objective of Context Knowledge modeling is a digital/computational representation of context that could allow designers to be interfaced with application programs like Vasari, Ecotect, DBLink, Protégé, Revit, dxf format, etc.

The research focuses on formal system specification because this is comparable in scope to a conventional requirements analysis using dataflow or entity-relationship diagrams and differs from conventional design specifications because it involves only the function of the system and makes no commitment to its structure.

CONTEXT KNOWLEDGE MODELING

Context can be evaluated a priori in the design process and be used as a starting point because it imposes constraints and at the same time offers opportunities, as in this sense it has always been taken into consideration by designers.

A broad range of parameters includes water, material consumption, atmospheric emissions, impact on site ecology, shape of district, density, accessibility, air quality, lighting, acoustics, inhabitants' age, etc. These external entities are related to internal ones through context rules (Figure 2).

A building cannot react to this contextual conditions only after its realization, but has to be built taking them into consideration by means of an inductive/deductive reasoning process. These processes essentially reduce the complexity of the solution for attaining the goals of architectural design. As the design process evolves, the solutions and the goals are modified and refined, until the desired behaviour is obtained.

The starting point for the work was the definition of entities by means of their formalization and the creation of rules for them, for example links among entities or their properties, reports, functions, etc.

In order to understand the 'Context' and its complex structure of relationships, any class of this ontology is divided into sub-classes and any entity belonging to these classes contains specific features. Context has been modelled in the following entities (Figure 3):

- *Environmental* ones - these can be divided into subclasses: existing constructions that can

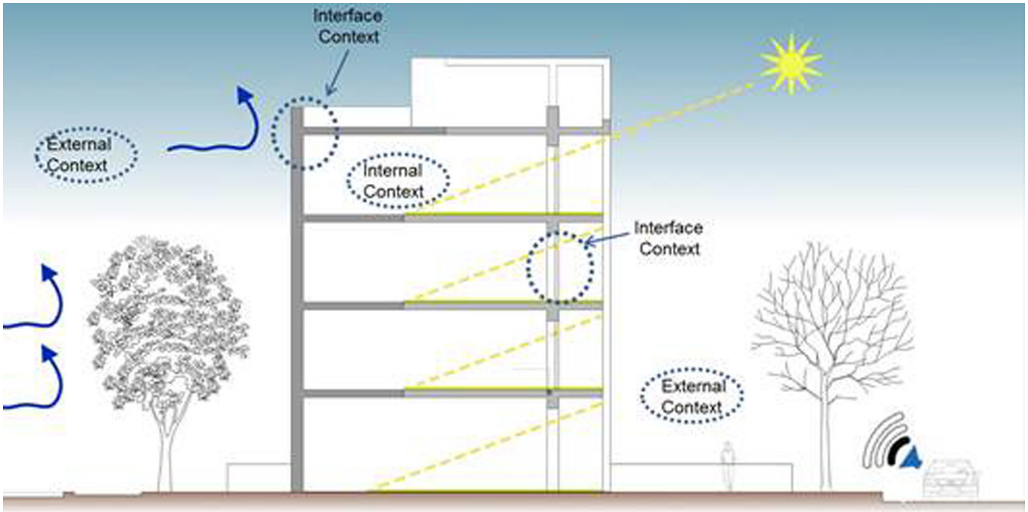


Figure 2
Influence of External Context on the Internal one.

be divided into: archaeological heritage as an open-air museum; restricted area, protected by law (antiquities act); element of cultural environment (in addition to built heritage and cultural landscapes); scientific data, etc.; existing buildings, i.e. all the buildings that already exist on the site, whether historical or not, but that influence Architectural Design; accessibility, which might be a pedestrian access, railways, or a driveway near the building site; morphology, which could be natural or urban, climate data which are typical properties that depend on location and affect the Architectural Design;

- *Social* ones were analyzed by studying the relations, culture and people that live in the place and their customs;
- *Economic* ones, containing the needs related to economic conditions, to financial funding of the project; cost of money in the country in which the designers are going to project and mortgage loans, the variation in the cost of money, the purchase costs of products.
- *Normative* ones, study the changes of the laws, the relationship between old and new and how they constrain the design project.

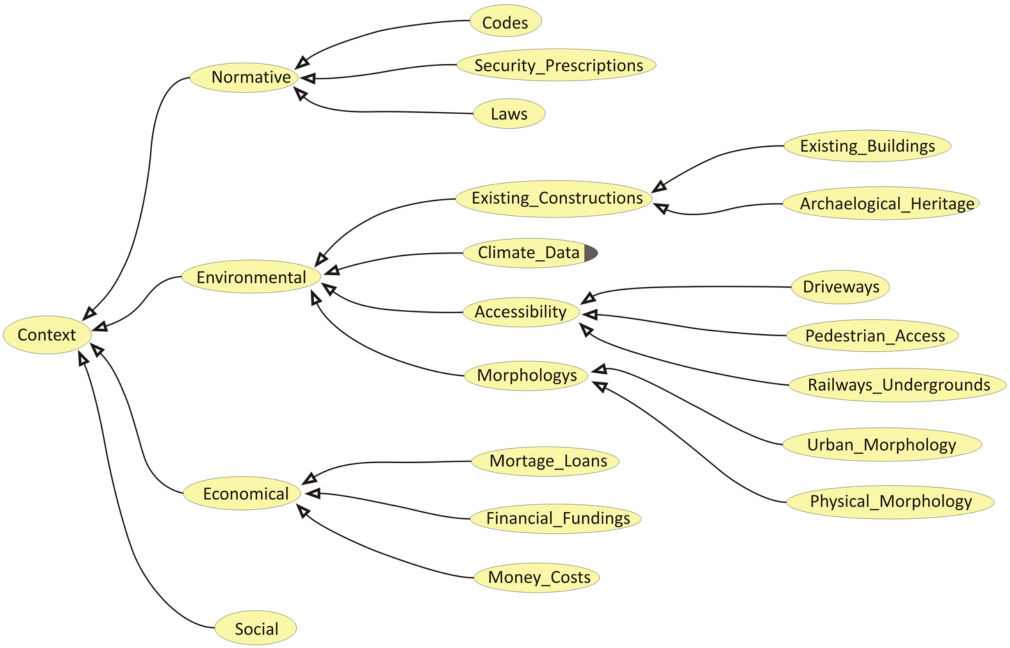
All these factors were analysed to find invariants to optimize the formalization of Context, because it plays an important role in the development of ideas that emerge, taking into account an interior, whether one's own or external knowledge. Each of these knowledge areas are part of the Design Process, because they influence all the phases of the Process (analysis, synthesis, evaluation).

By using a control system to support context knowledge with inference rules, designers could have a dynamic simulation of performance up to the early stages of Architectural Design.

"Ready to use" default entities can be instantiated or not according to the designers' interest. There is also the possibility to create new entities if during design process they are necessary to be taken into account, for the sake of example, new higher-performance wall types. This tool aims to enrich design freedom with the other opportunities, also with the possibility of implementing this model by adding new entities or/and switching off of constraints and default entities.

The research has analysed the critical issues related to Context Knowledge by contributing to the search for interactions between it and other 'realms'

Figure 3
Context Model Ontology.



of knowledge and how this might relate to the different actors involved in the Design Process.

The survey carried out has revealed that the relationships with Context are in need of simple rules in order to increase building performance. Starting from this point the computation of Context Knowledge can produce results that can be used in computing concepts of the environment and other related domains of the tetrahedron as design support.

The entities are formalized using OWL code, exportable in XML, and rules will be associated with each entity to define its characteristics.

The aim was to create a prototype to analyse and define the influence of Context in the Design choices. This was done by creating "clusters of Knowledge Context" (e.g. *Legislative*, *Economic*, *Social* and *Environmental*) studying how these are related to other Knowledge ('Product', 'Process', 'Actors') *Realms* and analysing the range of specific interest of each actor through classes and/or instances in which s/he may be involved.

An example of one of the rules of Context Knowledge is the relation between underground floors and geological report, because if we have unsecured ground there may be problems of failure inside the building after construction.

FORMALIZATION OF CONTEXT KNOWLEDGE

The difficulty to find a semantic level tool to support communication among applications and thus to enable Collaboration among Actors, has a two-fold aspect: on one hand, to match ontologies belonging to different specialist domains; on the other hand, to be related to the corresponding database of other actors' application programs.

Exploration starts with abstraction, and aims at gathering knowledge about understanding and conceptualizing contemporary phenomena within the environmental, normative, economic and social context. The complexity and variability of data collected through formal and informal interactions with the problem domain has not been simply defined.

From a computational point of view, requirements can be defined as functional expressions because they allow a set of building entities to be mapped as well as a set of goals to be obtained which express some of their quantitative and qualitative aspects. Specific values that satisfy a particular requirement, or a structured set of requirements, in a particular situation, represent the behaviour (or performance vector/matrix) of the class/es.

In this research, the primary source of data was an empirical exploration activity and a literature review carried out in parallel with the study of data collected and analyzed for the purpose of discovering concepts and relations that were subsequently organized into a tree of knowledge - a Knowledge Structure.

This research aims primarily at developing a computational model to improve the efficiency and quality of existing architectural design processes reasoning on the context Knowledge formalized.

These reasoning machines basically reduce the complexity of the architectural design solutions by pruning them so that designers can reduce their number due to their combinatorial exploration, architects can concentrate their efforts to attain goals of high quality design and innovative building (or shape or spaces...) while respecting the codes. As the design process evolves, the solutions and the goals are modified and refined, until the desired behaviour is obtained.

In order to formalize the influence of Context in architectural design the proposed structure of entities takes IFC classes into consideration while structuring them in a different way compared with the IFC ones, although it is based more on product data, and does not take Context into sufficient consideration. The research aims to consider Context information in a multidisciplinary process and is implemented in relation to the kind of building considered.

An analysis of 'Context' domain is presented in order to identify important real-life domain concepts and points to be improved in order to interface with computational support tools.

The exploration of context knowledge allowed the characteristics and the invariables of this domain to be discovered and a consideration to be made of its rules. Addressing existing processes, the targets of the exploration phase are:

- To describe the activities involved, functions and concepts and what kind of information is managed and what computational tools could be used during the process;
- To generalize practices and functions. This demands a critical eye being focused on the design process so that it becomes detached from single occurrences and focuses on those structures, or the invariables, which are common in most of the cases.

The Context Knowledge Ontology "defines and organizes classes, the entities and the significant relations among the various types of objects and features found in urban space to be used in the urban/building design process.

Context data specification has the function of identifying and describing context entities that will contribute to the assessment activities involved in Architectural Design. The aim of this phase is to create a footprint of context that captures the current condition of place and properties that influence architectural design. These components can be environmental (such as existing constructions, accessibility, orientation or location), social or normative (codes, laws, security prescriptions, etc.). While the description of context entities is important, the information about relations with the 'Product' is also a key aspect to be analyzed.

Considering an office room as a space component of a building (Figure 4) to calculate the heat transmitted from external walls we need to know the external temperature, irradiation, cloudiness, etc. The information about such elements contributes to the enrichment of the semantics of the building model by means of automatic reasoning mechanisms that operate on multiple components at the same time.

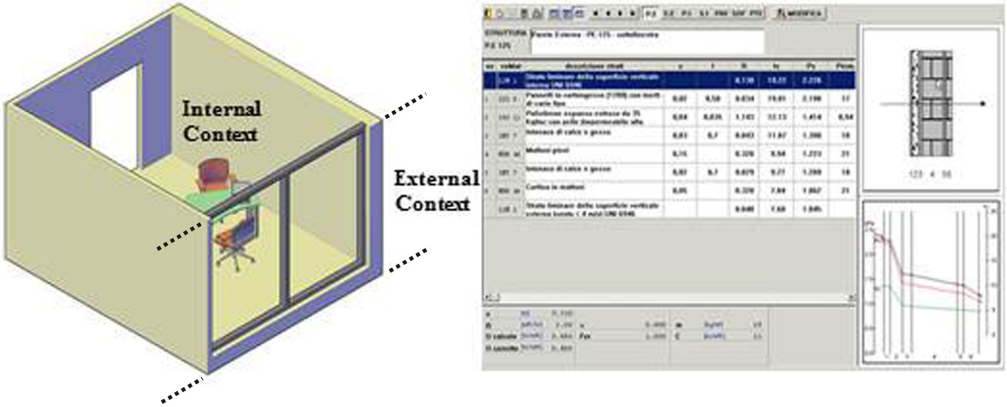


Figure 4
Office room and external wall and relations with' Context'.

The context components usually contain multidisciplinary information from various building phases. Moreover, the semantic expressivity of component models can range from simple object libraries that capture vocabulary, to semantically enhanced model based formalisms. Context data specifications are supported by a library in which the footprint of Product entities generated contains predefined concepts, relations, procedures, rules, etc.

As a result, the component representation embodies an understanding of building components that reflects the needs of the context in which it is used (Gursel, 2010).

The implementation and testing of the model was done using a case study.

Case studies emphasize the contextual analysis of a number of events or conditions and their relationships. For this research, the case study formed the main backbone of the research methodology, facilitating both the exploration of the problem domain and the development of the computational model.

The strength of a computational solution lies in its generalization and application to a wide range of existing processes and practices. The context characteristics, functions and information are discussed to develop computational solutions based on the model presented.

It is not possible to capture the entire range of context entities. However, the identification of the common and basic default entities facilitates the instantiation and analysis of Context, establishing the scope and development of this model. These functions are knowledge codification, data specification, data acquisition, data analysis and implementation.

The Context Knowledge Model takes into consideration the agreement on (and the codification of) the domain knowledge with the mutual agreement of the participating parties. The resulting codified knowledge is intended to be standardized only among the parties involved.

An example of Acoustic Context Rule (Fig.4) is that of Façade Sound Isolation. This model actually uses an in-depth search to find the entities involved and then to verify the acoustic isolation of a façade. It starts by finding the location of the building, then the acoustic zoning of the area to seek the maximum façade sound isolation value and then verify the rule. To verify the rule the algorithm searches all the values within the 'Product' entities and infers the role and compares it to the maximum façade sound isolation value. If it is true the system signals 'value verified', or else displays the string 'change values and verify again'.

PROBLEM SOLVING USING ARTIFICIAL INTELLIGENCE

Artificial Intelligence systems will be used to improve the performance and opportunities that the

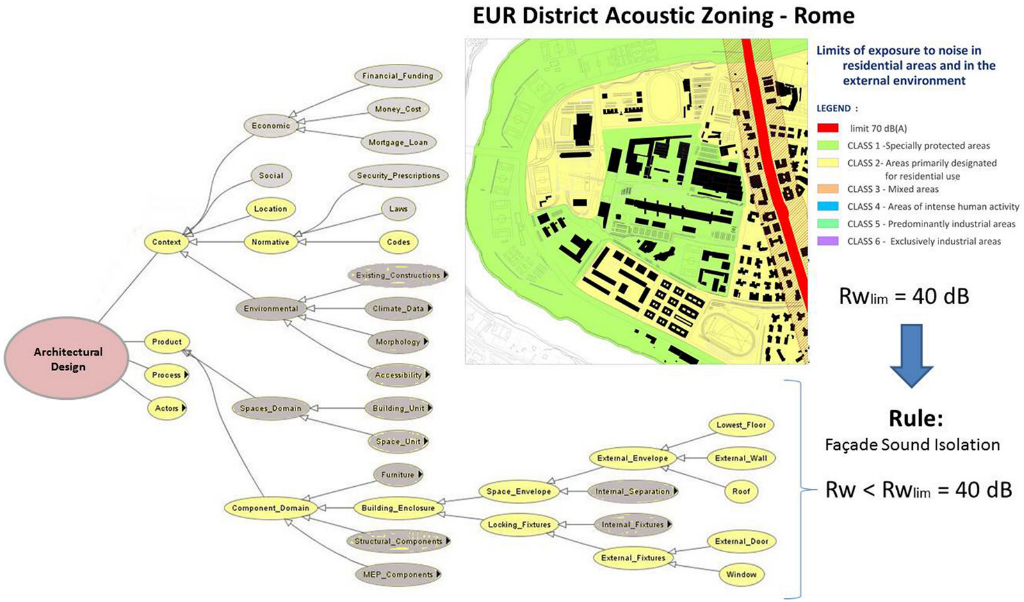


Figure 5
Acoustic zones near EUR - South Rome and Context ontology classes and an acoustic related rule.

$$R'_W = -10\log\left(\sum_{l=1}^{N}\frac{Sl}{Stot}10^{-R/10}+\frac{Aa}{Stot}\sum_{l=1}^{N}10^{\frac{-na,k}{10}}\right) - K$$

system offers, because they could help to minimize the cost of a set of texts, the size of the set, to reduce the size of training set, to simplify input, to improve the performance of the system. There are still no results and applications for this research, although the various types of systems were analyzed in order to assess which of these systems can be used in architectural design.

Informed research allows solutions to be found more efficiently. This type of research takes advantage of the use of heuristics in problem solving. There are various types of algorithm that use this approach to guide heuristic search such as: greedy best-first or A*. Other algorithms use a 'relaxed' approach such as simulated annealing or genetic algorithms. These types of studies are based on the assumption of a study conducted in a space of states, using specific heuristics. However, there are other 'more efficient' ways that allow you to solve a wider range of problems and which can be most useful in the field of research presented in this paper such as the use of a factorized representation for each state, and a series of variables, each of which has a value. A solution to the problem could obtained when each variable has a value that satisfies all the constraints on it. A problem that is described in this way is called CSP (Constraint Satisfaction Problem). CSP search algorithms exploit the structure of the states and use general purpose heuristics instead of specific problems to find the solution of complex problems. The main idea is to eliminate large portions of the search space, identifying combinations of variables and values that violate constraints (Russel and Norvig, 2010).

To solve a constraint satisfaction problem a space of states and the concept of solution have to be defined. Each state in a CSP problem is defined on the basis of values assigned to some or all of the variables, (Xi = vi, Xj = vj .....). An assignment that does not violate any constraints is called consistent or legal advice. An assignment is complete if all variables have an assigned value and a solution of a CSP is a complete and consistent assignment. An assignment is partial if it mentions only certain variables.

An example where it could be applied in CPS is the analysis of design constraints imposed by the context of the project. The entire study is constituted by several checks, each of which can be modeled through a variable whose value depends on the location of the building. Constraints can determine if, for example, the wall complies with the thermal or acoustic characteristics of the site.

A useful algorithm for structuring logical inferences is called model checking which is a direct implementation of the definition of logical consequence: that is it explicitly enumerates the models and verifies that α is true in every model that contain the Knowledge Base. The models are represented by assigning true or false to each symbol. This approach is currently being used for project management and reporting of Context and Product.

AI inference rules may be needed to make research more efficient, for example Modus ponens: $(\alpha \rightarrow \beta, \alpha)/\beta$ notation means that, whenever you are given the formulas $\alpha \rightarrow \beta$, you can infer the formula β or eliminate thereof and according to which a conjunction can infer any of the joints (Russel and Norvig, 2010).

The goal of using Artificial Intelligence techniques is to minimize the number of soft clauses that are false in order to satisfy all the hard clauses. It allows the clauses to be weighted, with the objective of minimizing the sum of the weights of the false and hard clauses.

CONCLUSIONS

Decisions made in the first stage of a Design Process are very important and may influence the final result of the design. It is therefore necessary to understand Context in order to reach better solutions more rapidly and reduce costs (Penttilä, 2006). This formal method of Architectural Design could provide an intuitive feedback to help designers to facilitate the basic comprehension of Context designers' needs, to visualize feedback in performing simulations. Digital simulations with the high-tech tools can complement the low-tech tools in order to enhance the investigation of the phenomena in a specific site.

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