Building Design and Simulation by linking Product and Functional Use

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Abstract: The quality of buildings, in a long-term perspective, belongs to four aspects: the Building Object, the Users, their Interactions and Context.
Based on this assumption, we model building process knowledge in architecture, engineering and construction (A/E/C) sector, as well as occurrences, which dynamically happen both in the built environment and in the building site.
Studying the most common information standards in A/E/C sector, namely IFCs structure (and BIM proprietary application programs), we can observe that they are a product information model (PIM) developed by means of architectural space / building components approach. It is successful in terms of data exchange and information interoperability between programs, but not intended for a higher abstraction layer: the human understanding or semantic-based programs. This lack of semantics is reflected in the modelled/constructed buildings, for instance once it is required to simulate occupant behaviors in terms of usage, safety and comfort.
There also is an urgent need for tools able to link and translate business rules and project processes to check where business processes are not following building policies and rules.
With the aim of improving the quality of buildings and their use, this paper explores a method for representing and linking building process, product, and their functional use. This research group has formalized a general structure of building knowledge modeling to share semantics, not only information, by means of ontologies.
Now the research group is working on early IT implementations to support logic synchronization between software for designing activities and software for authoring design.
A hybrid approach for computational technique has been identified, combining (big) data-driven algorithm with ontology-based context reasoning, in order to achieve both, the best performance from intensive data-driven methods, and the finest adaptation for ontological context awareness.

Key-Words: - Building Information Modelling; Building Knowledge Modelling; Knowledge Management; Process Engineering; Meta-design Ontologies.

1 Functional Program vs. Product Design Issues in Buildings

A shared goal, typical of all A/E/C industry products, is to functionally facilitate its direct and indirect users' activities, being aesthetically pleasing [1].
With the aim of improving the quality of user experience, this paper explores a method based on process-product knowledge, formalized to support logic synchronization between the planning of activities and design of infrastructures.
In order to get this overall performance, buildings and cities behavior has to meet various technical and non-technical requirements (physical as well as psychological ones according to desires of owners, users and society at large.
Research in this field will be seeking to increase the quality of building production, by means of open, participatory approach and exploiting the most advanced technologies.
In terms of technological solutions, the product knowledge has been fairly studied and a number of modeling techniques have been developed. Most of them are tailored to specific products or specific aspects of the design activities.
Current research on A/E/C product modeling can be classified in two main categories:

- Geometric and component/functional modeling, mainly used for supporting parametric detailed design;
- Knowledge and semantic modeling, aimed at supporting conceptual aspects of designs.

Specifically, on the need to manage the symbiosis between building and its functions, so that computers can support every phase of construction (e.g. *Solibri* program) it is necessary to have information models based on an adequate knowledge representation, able to be computable.

This kind of knowledge, oriented to solve complex technical problems, cannot avoid qualifying the product building through its relationship with the context and with the actors.

In term of social contributions, on the other side, we need to clarify roles and identify responsibilities of actors involved along the building life cycle, from the client to designers, providing advanced support systems for ‘actors’ participation from the early stages of design concepts.

The BIM methodology/technology assumes that there is a client/owner/designer able to reduce the level of ambiguity in the definition of requirements.

Owners-Client, especially if they must also manage the constructed facility, are the largest beneficiary of the process-product model development, because of their risk-based reasoning approach leads to the optimization of contract management.

Designers, challenged to become more aware of – ill-predefined - product and process models, are the key to the spread and development of the most advanced and appropriate technologies.

An open area of research works on the interface between designer and tool, to enable: first to clearly face pre-defined patterns and then to customize them while using the software they are familiar with.

Final users, generally, as well known, play a vital role in Architecture. How do they actually use a building? How do they satisfy an experience of a building?

Till now their needs have been taken into account by means of an *average* behaviour” and an *average* aim. The “average” values are the *standards* values derived from statistical study.

Looking at what happened on structural engineering domain regarding structure dimensioning by Building Code paradigms:

- First, *average* values for loads, strength of materials, behaviour models have taken into account;
- Afterwards, the statistical combinations of these *average* values were considered;
- At the end, FEM programs of structure have been validated and used to calculate safety conditions.

We are witness of the same Building Code evolution to evaluate users’ satisfaction of a building and how they actually use a building. Now there are researches to model and simulate the users’ building use by means of agents, each of these having its own behaviour. The problem has now addressed to a new objective: how to represent human behaviour of agents? Planners' traditional approach consists in entering planned processes (expertise, technical regulations, best practices, etc.), in an architectural schema [2, 3].

However, those processes are correct only if the planner can correctly anticipate and inform the usage of the building by different building user groups.

We think that if organized in a proper way, it is possible to represent usage scenario, predicting activity inconsistencies and evaluating the performance of the building in terms of user experience.

2 State of the Art in Meta-Process Modelling Research

Building Modelling is not an objective process, but rather subjective, aimed at very specific purposes that depend, first and foremost, on contractual typology. On process models there are a lot of misleading quarrels, in the sense that many models have always appeared very reductionist and simplistic in relation to: the complexity of reality and the intentions of different actors involved.

Many applications use process information, including production scheduling, process planning, workflow, business process reengineering, simulation, process realization, process modelling, and project management.

There are at least two problems with the way all applications typically represent process information:

- They use their own internal representations, therefore communication between them, a growing need for industry, is nearly impossible without some kind of translator.
- The meaning of the representation is captured informally, in documentation and example, so little automated assistance can be given to the process designer.

In terms of Process Knowledge Modelling, at the state of the art, it is important to refer to some on-going researches at International level:

NIST CPM*:* A design repository project at NIST attempts to model three fundamental facets of an artifact representation: the physical layout of the artifact (form), an indication of the overall effect that the artifact creates (function), and a causal account of the operation of the artifact (behavior).

The NIST Core Product Model (CPM) has been developed to unify and integrate product or assembly information [4]. The CPM provides a base-level product model that is: not tied to any vendor software; open; non-proprietary; expandable; independent of any one product development process.

The buildingSMART: Standards for processes [5], specifies when certain types of information are required during the construction of a project or the operation of a built asset.

It also provides detailed specifications of the information that a particular user (architect, building service engineer, etc.) needs to have at a point in time and groups together information that is needed in associated activities: cost assessment, volume of materials and job scheduling are natural partners.

Thus, the buildingSMART standard for process offers a common understanding for all the parties: when to exchange information and exactly what is needed.

The linked Model View Definition - MVD - turns the prerequisites and outcomes of the processes for information exchange into a formal statement. Software developers can take the standard and specific Model View Definitions that derive from it and incorporate them into their applications. The detailed information for this is described in the ISO standard: ISO 29481-1:2016 Building information modelling -- Information delivery manual -- Part 1: Methodology and format [6].

ISO 29481-1:2016 specifies a methodology and format for the development of an Information Delivery Manual (IDM) that unites the flow of construction processes with the specification of the information required by this flow, a form in which the information should be specified, and an appropriate way to map and describe the information processes within a construction life cycle.

'Whole Building' Design: The National Institute of Building Sciences provides a 'Whole Building' Design Techniques and Technologies for strategic, overall decision-making approach [7]. The scales deal with both demand (occupant requirements) and supply (serviceability of buildings). They can be used at any time, not just at the start point of a project. In particular, they can be used as part of portfolio management to provide a unit of information for the asset management plan, on the one hand, and for the roll-up of requirements of the business unit, on the other. The ASTM standard scales include two matched, multiple-choice questionnaires and levels. One questionnaire is used for setting workplace requirements for functionality and quality. It describes customer needs—demand—in everyday language, as the core of front-end planning. The other, matching questionnaire is used for assessing the capability of a building to meet those levels of need, which is its serviceability. It rates facilities—supply—in performance language as a first step toward an outline performance specification.

A set of tools was designed to bridge between "functional programs" written in user language on the one side and "outline specifications and evaluations" written in technical performance language on the other. Although it is a standardized approach, it can easily be adapted and tailored to reflect the particular needs of a specific organization.

To set up an information modelling process since briefing phase, implies reasoning primarily on the building functions and on the physical environmental solutions, such as energy modelling or usage planning. Some years ago, researchers turned on knowledge instead of information [8, 9] and our researches were inspired by this approach.

3 Design by means of simulations

On this basis, few current research projects [10, 11, 12] have been involved in the development of conceptual modeling approaches.

Present research framework outlined in this paper starts from occupancy analysis (users profiling, context and reciprocal interaction) in order to collect Behavioral Knowledge. A suitable structure for formalizing project-process semantics and incrementally populate it have been studied.

The core of the modelling task is to ensure an efficient connection between building process, product, context and users, in order to support design and evaluation, by means of both static simulation (Data-driven and Ontology-based) of a specific artefact, and dynamic simulation of a contextualized use process (Agents+AI).

3.1 Use-process simulation tools

As agreed by the most scientific literature in the field, a simulative model is based on two main components:

- A static component, representing a specific and unique system status based on all formalized entities, including all the instances present in the instant T0,
- A dynamic component, able to perform the changing of the entities state from the system status T0 to T1.

In the last years, agent-based modeling approaches have been introduced in this research field, aiming at simulating users' behavior in built environments by developing a series of autonomous entities – the

agents - each of which interacts in an autonomous way with the other users and with the environment surrounding it.
This kind of simulation approaches, such as "narrative approach" doesn't allow a prediction but the pre-defined scenario visualization.
According to Kalay [13], agent-based models has shown to be highly requiring in terms of computational resources and not enough expressive in the simulation of events in which the users-agents have to make context dependent decisions and behave in an interleaved way.
The simulation model here presented integrates two main modules:

- Use Process Knowledge which structure has been presented in a previous paper [14], linking, in a homogeneous computational environment, BIM to higher level semantics;
- Simulation engines to perform and visualize the effects of the model status change.

Based on this kind of model, a hybrid Agents based simulation model is investigated.
Agent are associated to AI resources, that reside not only in the Actors' Knowledge Bases, but opportunistically in other entities (Context, Product, Process), reducing computational loads and enabling inference engines to process rules-based reasoning.

3.2 Context Awareness

Context consists of not only physical space like environment, but also cultural, psychological, technical, etc. [15] or any information that can be used to characterize the state of an entity [16]. Entities can include a person, an object, an environment, an application, or a device that interacts between them and the user.
Proposals to model context can be integrated with human activity models provided with semantics.
According to Rodriguez [17], as time is not a feature inherently treated in knowledge-driven approaches such as logic-based systems, having hybrid methods with a first data-driven preprocessing stage appears to be the right direction to benefit from both data- and knowledge-driven computing paradigms. As ontological reasoning can be computationally expensive, this type of combination would achieve the best performance and efficiency from (time-dependent) data-driven methods (that can be more efficiently computed) and obtain the best adaptation for context awareness in each case.
It is important to note that Web Ontology Language 2 (OWL2) is powerful for expressing knowledge entities, context entities and relations among entities. However, OWL2 is insufficient to model context relations and rules with the form of cyclic relations.
Therefore, the ontologies discussed require an integration with a rule language - such as Semantic Web Rule Language (SWRL) [18] or SPARQL Inference Notation (SPIN), now SHACL [19] - in order to express more complex and real-life context rules.
The combination of Data language with Rule-based language improves the reasoning capabilities.
Rule-based languages enable definition of consistency rules, reducing ambiguity in the context information and thus maintaining and improving the information quality. For instance, SWRL extends the semantics of OWL and defines antecedent-consequent rules and built-in operators (math, comparisons, string and time).
As a concluding remark, we can clearly point out that the integration of different methodologies (i.e. data-driven and knowledge-based ones) could help overcome current limitations in scenarios with several actors, providing semantics to social activities, user identification (according to behavior semantics), and so forth.
Current hybrid approaches such as Gomez-Romero et al. [20] have shown that these types of combinations can enhance the response of data-driven approaches as the environment complexity and the context awareness needs increase.

4. A framework to formalize spaces and human behaviour

The model for simulation of the interaction between humans and environment presented here outlines an implementation pattern for integrating BIM space and physical characteristics by behavioural knowledge, intended as a semantic structure capable of representing the entities and their relationships between activities-actors-context and places [21].
Compared to current research in the field, the present approach to represent Behavioural Knowledge includes among others formalization of user personal aspects, like Personality Typologies, classes profiling and expected behavioural patterns.
A hybrid approach for computational technique has been preferred, combining (big) data-driven algorithm with ontology-based context reasoning, in order to obtain both, the best performance and efficiency from intensive data-driven methods, and the best adaptation for ontological context awareness (including unexplored context capabilities and objects adaptations).

4.1 Use and Behaviour Knowledge

'Use Process Knowledge' is represented by means of Use Process Ontology, a structure based on Use Process Entities, qualified by a system of Use Process Rules [14]. On one hand these process rules govern activities planning and on the other hand they control the relationship with the rest of knowledge realms: who does what, where, when and how.

Use Process Knowledge can be described by means of process classes, at different levels of aggregation:

- Use Process Actions: elementary class entities structuring the Use Process Ontology. They represent the process based on user's minimum ergonomic function.
- Use Process Activities: a set of Use Process Actions structured in time and space, oriented by the functional programme. They qualify the relation between users and building (spaces, components, facilities, equipment, etc.).
- Use Process Rationale: aggregation of Use Process Activities. The importance of representation for use rationale has been recognized but it is a more complex issue that extends beyond artefact function. It is function of social-economical-environmental sustainability.

- Events: particular process entities, "milestones" that occur in the dynamics of the activities.

Emergencies necessary to structure the causal and dependency relationship between Use Process entities".

5. Implementation process and expected results

This section reports on a theoretical framework and some early implementation patterns developed in the general framework of an on-going research aimed at the definition of a new approach to support assistive systems for management and performance simulations.

To model and test knowledge related to the user behaviour in a building environment we need:

- Spaces that are characterized by physical parameters related to environmental comfort but also with space-time Functional aspects, Potentialities or Behaviours, Capability or Action [22]];
- A Use Process Knowledge structure that includes Skeleton Activities and Intermediate Activities;
- An Agent-based simulation, enhanced by associating agents with AI resources (upper ontology level), that reside not only in the Actors' Knowledge-based systems, but also in other Planner traditional approach conceives at the beginning of planned processes expertise, technical regulations, best practices, etc. in an architectural schema [2, 3].

However, those processes are correctly performed only if the planner can rightly anticipate and inform the usage of the building by different building users.

Evidently this is a risky task, relying on designers limited and implicit knowledge, since the human behaviour in a building is highly non-deterministic and not a-priori definable.

To support this kind of operation, we rely on a general structure of knowledge representation known in the scientific community developed by DaaD group that works to extend its application fields [23].

For implementing this theoretical model, we are using ontologies plus agents (upper ontology level) in order to model, the design use events entities, physical or abstract, and their space-time relationships structured by means of M-P-R meanings, properties (defining their state) and rules (relations, reasoning rules, consistency, best practices) [24].

The new challenge now is to represent by means of the same knowledge structure M-P-R, the right entities and their relations, in order to manage in a CAAD environment, human behaviour simulation needs to be taken into account including psychological aspects.

Analysis, checking, evaluation and control of concepts associated to specific entities are performed by means of inferential engine demons, with deductive 'If-Then' type procedures.

A system of engines will work on a deductive layer overlapped at the actual BIM level, allowing the designers to use in a coherent manner different levels of abstraction.

The implementation steps are:

- Represent Design Knowledge of Event Ontology (e.g. expressed in OWL language);
- Connect Event Ontology with actual BIM, or IFC (by means of API, or using Beetz [25] transcription of IFC in OWL) ;
- Connect BIM+ Ontologies with a Narrative environment (e.g. BPM, Virtools, etc.)
- Find out in the Semantic Web community or build an inference engine to perform the user's behaviour.

The dynamic and semantically-specific representation together with Inference and Simulation Engines are able to predict human behaviour, so coherent/favourable situations will be evaluated by means of a set of constraints, and will be highlighted and managed in real time.
At the same time, this model allows actors to assess alternatives, more consciously reflecting on the consequences of their intents.
By this way the impact of a networked ontology makes actors more aware of overall design problems and allows them to operate more participative and shared choices.

6. Conclusions

This paper reports on theoretical contents and some early implementation patterns developed in the general framework of an on-going research aimed at the definition of a new approach for modelling and testing knowledge related to the users behaviour in a building environment, oriented to support assistive systems for management and performance simulations.
A specific methodological and technological solution is sketched. A key role in the implementation path of the proposed Building Knowledge Model (BKM) is played by the realization of efficient links between ontology modelling technologies, and actual Building Information Models (BIM).
BKM represents rules about processes in the same way as the processes evolves, and uses a formalism that supports automated reasoning.
Introducing and enhancing reasoning mechanisms it will go beyond the potential of existing commercial tools for supporting decision-making activities.
The proposed knowledge-based system supports process traceability and, consequently, allows responsibilities recognition and re-usable experiences collection.
The possibility to coordinate design process between different actors (including clients, final users, etc.) and to evaluate the building quality before its construction will increase the chances for the client to be satisfied and will provide more guarantees to success in terms of future efficiency and performance.
The research agrees on introducing hybrid approaches to take advantage of each technique's best strengths. Combining ontology-based context reasoning with data-driven algorithms has shown to be a promising path to be explored.
At present the proposed general framework has been defined a framework implementation that can count on a limited number of building entities formalized by means of current ontology editing systems in order to be used for design reasoning, using the large family of ready-built inference engines and information extraction tools.

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