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Users and Space Behaviors: A Complex Relationship. A General Framework for Integrating Innovative Technologies with Use Simulation

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Abstract

Integrating innovative design technologies with simulation of building uses for refurbishment, valorization, new construction, and operational management, it is crucial to conceive responsive and intelligent spaces according to the dynamic needs of their occupants. Users' presence, both humans and agents, must be integrated into the actual simulation models for evaluating and enhancing the ability of the designed spaces to host new uses and, eventually, to adapt itself accordingly. BIM enables – and is limited to – advanced simulations of building behaviors such as energy, structural, and acoustics, but lacks the ability to handle space use processes. This research focuses on the conceptual representation of the next generation of building models, which will be able to evolve the IFC standard by adding the AECO semantic values, with the occupant's well-being as a central reference for analysis. This paper contributes to sketching a theoretical framework within which it is possible to compute the interaction between Users and Spaces according to the context in which the reciprocal behavior occurs. An innovative methodology is proposed based on a multilayer organization: (i) Object-based for project data automation (BIM); (ii) Ontology-based for semantic reasoning (IFC modular enhancement for inferences); (iii) Cognitive-based for comparing goals and exploring consequences /side effects of design choices (Semantics Engines/Agents). The implementation pipeline checks some crucial aspects of the integration feasibility to engineer design knowledge and reasoning, and illustrates the automation criticalities for providing the existing BIM system the semantics required to achieve the User/Space symbiosis goal-directed behavior simulation.

Keywords: Design Semantics, Use-process Knowledge, BIM, Human Behavior Simulation, Cognitive Computing.

1. Introduction - Rethinking Spaces to Enhance Well-being

Most European buildings currently in use have been constructed without or, in the best cases, based on architectural and psychosocial conceptions that reflect goals, knowledge, sensibility and an approach to sustainability over fifty years old. The debate concerning the functional optimization or reuse of existing buildings, including questions about their potential change of use or their general occupancy, has been ongoing for a long time.

Controlling the indoor quality is more than a sum of mere requirements: it also relies on the active participation and satisfaction of human users. Individuals can create a healthier living environment by implementing energy-efficient practices, enhancing air quality, conserving water, and adopting waste management strategies. This can be achieved by optimizing lighting, selecting indoor plants, incorporating smart home technology, and other similar measures. Engaging in these domains not only preserves personal health and well-being but also contributes to broader

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sustainability goals. [1].

Conditions which allow a person to achieve an integral well-being, both individually and collectively, from an Architectural, Engineering, Construction and Operations (AECO) point of view, also depend on the capabilities and potential adaptations of the built context, intrinsic of the designed manufact, explicit or potential (e.g. space layout, technological components, equipment, etc.) [2]. In order to improve the quality of an architectural artefact, a central task for multidisciplinary design teams is to test tentative design solutions and see how well they work "in practice" before, during, and after the construction: from digital model to real world.

At present, the task of predicting and assessing if and how an existing environment will effectively host new uses and/or users, evaluating the impact on well-being, is still barely supported by suitable models and is usually left to designers' expertise and imagination. To enhance control over the final design product, the quality of the use process is a key element for boosting well-being and productivity in properly renewed spaces.

Researchers are called to study methods and develop tools to support decision-makers in the modification process of the built environment - new realization, refurbishment and change of use, conservation and maintenance - according to humans' operational needs [3].

The present "concept paper" aims to contribute to sketching an enhanced workspace by extending and integrating a set of previous authors' works [4, 5, 6], rather than serving as a report on a case study. This workspace facilitates the computation of the "dynamic" interaction between users and spaces linked to the specific context in order to address inconsistencies between "real" and "simulated" use process assessments.

The 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 populating it has been studied. Advanced use process simulation is fed by data and information captured from the real world through a reverse engineering process (big data approaches), which is consequently formalized in structured knowledge (ontology-based approaches).

The aim of the general framework proposed for knowledge modelling tasks is to ensure an efficient connection between the building process, product, context and users [6], 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), overcoming the limitations of the existing BIM models.

2. Limits of BIM for Use Simulation

2.1 BIM: A Product-Related Model

The introduction and widespread use of Building Information Modelling (BIM) technologies in professional design studios is causing a significant change in designer habits. These technologies enhance designers' ability to anticipate and manage building-related problems and conflicts commonly arising during subsequent phases, such as construction, use, maintenance, reuse, or demolition. This happened because the multidisciplinary decision-making process, complex and highly recursive in some aspects, relies on how product-related knowledge is modelled for interoperation among the current design tools.

By examining the predominant standard in the field of BIM, namely Industry Foundation Classes (IFC), it becomes evident that computer-aided architectural design (CAAD) tools have been created using a space-components product strategy. This method has been shown to be effective in facilitating the flow of data and ensuring compatibility of information between different software programs, along with, according to the current diffusion, the existing building and its Digital Twin. However, these tools lack semantic capabilities, which is evident in the simulated buildings. This becomes particularly evident when attempting to replicate the buildings' behavior in terms of usage, safety, and comfort.

The use of current standards, techniques, and technology to predict human behavior within buildings during their use remains a longstanding challenge for knowledge engineers and building designers [3]. The support of automated reasoning, based on explicit semantics, will allow designers to assess alternatives, more consciously reflecting on the consequences of their intentions.

2.2 Enhancing BIM for Well-being Simulation

Building simulation is a common practice in the construction sector. It has grown substantially in the academic world and the building industry since its emergence over three decades ago. Research in the building simulation field is

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abundant, with specific regard to modelling the behavior of human agents in routine business activities or even in egress situations [7, 8]. Among available design tools and methods, it has been largely discussed in literature that recent BIM models support sophisticated building behaviors' simulation, such as energy, acoustics, and lighting, although at the state of the art, this paradigm is not able to manage both users' activities and space use-process [6].

Only recently has the focus been shifted to analyzing the overall patterns, semantics, and complexity of daily human activity and needs within buildings, as well as the relation of these activities to domain-specific enterprise processes, controlling buildings' operation and performance. On this basis, a few, but growing, current research projects [9, 10, 11, 12] have been involved in the development of conceptual modelling approaches in order to enhance simulation of existing artifacts concerning their potential optimization (re-)use. Anyway, at the state of the art, the definition of user requirements, a milestone for achieving the aforementioned goal, still relies on static methods and models, defined a priori by a few knowledge engineers. In order to evaluate well-being in built spaces, simulation models need to manage complex semantics, including BIM-based environmental physical parameters, and formalized users' personal aspects, like personality typologies, traits profiling and expected behavioral patterns.

For extending BIM/IFC toward a more sophisticated automation of designers' tasks, the presented research aims at modelling and testing knowledge related to the user behavior in a building, by means of the following steps:

1. Spaces that are characterized by physical parameters related to comfort but also with space-time Functional knowledge-based structures, Capability or Action [4];
2. Users, defined by means of an agent-based simulation, enhanced by associating agents with AI resources (upper ontology level), that reside not only in the actors' knowledge-based structures but also in other *Realms* (context, product components, process) [5];
3. Use process knowledge-based structures [6] that relate users to spaces and vice versa; it includes skeleton activities and intermediate activities [10].

As previous steps include semantics to simulate human activity, context awareness techniques, in terms of space and time, become a central part of future modelling systems. To this aim, in the following section, the authors review the theoretical foundations of modelling and computing the dynamical interaction between users and building spaces, starting from the origins in cybernetics, recalling the cognitive vision of the context, oriented to define behavioral knowledge of users in the built space.

Although this is not a review work, we wanted to place a special emphasis on a critical and original analysis of a specific aspect of the state of the art. Namely, with the goal of presenting our general framework for behavior simulation (see sections 4 and 5), in the following section, we classified and investigated two different categories of paradigms for computing behavioral knowledge and cognition of the actor in a context.

3. Interaction Between Users and Environment: Cognitive Vision of the Context

3.1 The Environmental Behavior

According to Ecological psychology or "Field Theory" by Kurt Lewin, founder of the experimental *Social and Environmental Psychology* (1936), the field of social and environmental forces influences behavior.

Lewin's Behavior Formula: B = f (P, E)

His "Reciprocal Determinism" theory, defines "Behavior" as a function of the "Person" and his/her (physical/social) "Environment", where Person, Environment, and Behavior influence one another in a dynamic way (Fig. 1).

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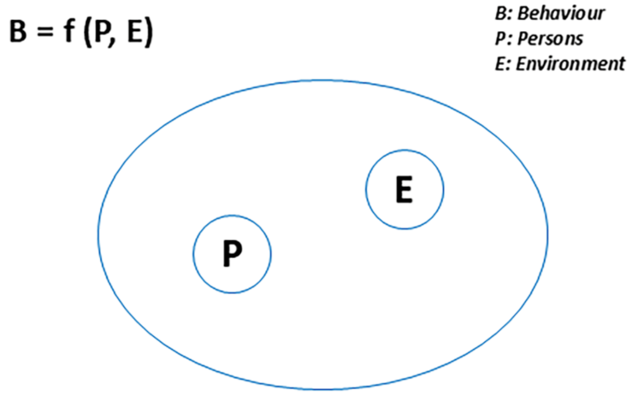

Figure 1 - Behaviour as a function of Person, Environment and their relations

Based on this assumption, he started to develop a systemic view of environmental behavior. «the environment does not only cause behavior, but is also influenced by behavior»:

Persons ---> MODIFY ---> Environment

Persons actively search for situations that fit their aims and personality:

Persons ---> SELECT ---> Environments

Spreading Lewin's definition to a digital modelling perspective, oriented to design and to pre-figurate phenomenon in AECO sector, in a virtual, non-existing-yet world, we assume to extend the "Person" definition toward the "User" that includes also non-living characters, like agents, and the "Environment" definition can be better specified, and subsequently computed, by dividing it into two further knowledge domains (knowledge-based structures): Space and Context.

One, that of "Space", concerns the eminently physical, ergonomic, and performance aspects, while the other, the "Context" [13], concerns the cultural and social domain of existence.

The three domains (knowledge-based structures) interact and influence each other: Behavior is a function of Space, User, Context (Fig.2).

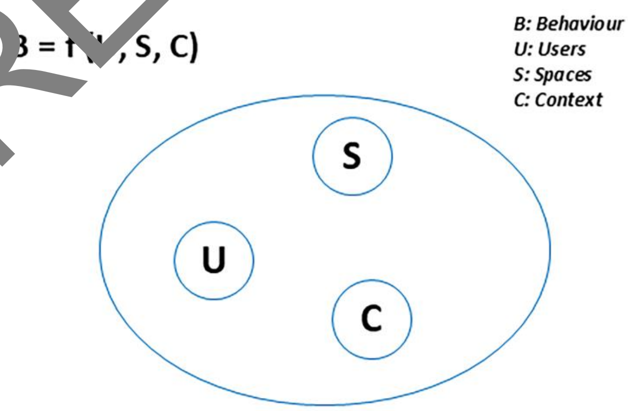

Figure 2 - Behaviour as function of User, Space, Context and their relations.

Context consists of any information that can be used to characterize the state of an entity, and can be defined as a complex relational system of entities, assuming different meanings and oriented to general aims.

Users' personality, attitudes, expectancies, goals, and competencies are influenced by the social and natural environment. How people "live" a building, their holistic sensation passing through and around its spaces and the

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perceived quality, relies on two aspects:

- *Functional* ones − anthropometric movements and perceptions − e.g. can be represented by Relational Structures and Inference Engines;
- *Soul ones* - personal beliefs and social and cultural habits - e.g. can be represented by intelligent agent-based models simulating individual human behaviors.

Although personality makes users unique and different from each other, in today's simulation practices, a diffuse classification approach is adopted for pragmatic aims, inspired by the commercial goods and services industry, based on an opportunistically oriented and effective *Personality Typologies* definition. For instance, "Consumer" typology and "Life-style" typology use psychological and other features to describe a group of persons: these are not personality theories or traits in the classical psychological sense, e.g. not stable over the lifetime.

In advanced Agent-based business simulation models, such typologies often include consumption patterns and behaviors as a basis for classification. Of course, a clear distinction is required between characteristics used for classification, and related behavioral characteristics, e.g. different variables can be focused on the same or different typologies: demographics, knowledge, environmental concern, norms, activism, shopping motivations, behavior, etc.

3.2 Cognitive Vision of the Context

As discussed in [5], a fundamental task for modelling a general domain of knowledge related to people acting in a space is the effective representation of the users' cognitive vision of the context (and vice versa). Since there is no universally accepted agreement on what "Cognition" is, different research communities have developed different perspectives on the matter: artificial intelligence (AI), image processing, developmental psychology, neuroscience, and others in cognitive robotics and autonomous systems theory.

Vernon [14], for narrowing the technical field of quest - specifically the definition of "cognition" and, for our research aims, of the "*cognitive vision*" - raises a couple of relevant questions to be addressed:

- How can we engineer knowledge and understanding into a system, providing it with the semantic information required to operate adaptively and achieve robust and innovative goal-directed behavior?
- Does a cognitive system necessarily have to be embodied (in the sense of being a physical mobile exploratory agent capable of manipulative and social interaction with its environment, including other agents)?

In order to start reflecting on the possible answers about computing the cognition, follows a step back to the "recent" origins of Cognitive science.

3.3 Cognition and Computers

Cognitive science has its origins in *Cybernetics* (1943- '53), following the first attempts to formalize what had, to that point, been metaphysical treatment of cognition. The intention of the early cyberneticians was to create a science of mind, based on logic. The initial wave in the development of a science of cognition was followed in 1956 by developing an approach referred to as *Cognitivism*.

Cognitivism asserts that cognition can be defined as computations on symbolic representations, i.e. cognition is information processing: rule-based manipulation of symbols. Much of Artificial Intelligence (AI) research, recently reborn and exploded, has been carried out on the assumption that the cognitivist hypothesis is correct.

Its counterpart in the study of natural biologically-implemented (e.g. human) cognitive systems is cognitive psychology, which uses "computationally characterizable representations" as the main explanatory tool.

More recently, Gero [15], a researcher with a deep CAAD background, aimed to extend our understanding of what kinds of knowledge we can expect our computational tools to have, and how systems that have a range of kinds of knowledge might perform differently.

Gero refers to such objective knowledge as "third-person knowledge" in that the Person (better the User, including humans and agents) who produced the knowledge is not required to be there when that knowledge is used by another Person/User. "Third-person knowledge" can be distinguished from "first-person knowledge" by defining it as the kind of knowledge developed through the interaction of individuals with their world, or, according to our definitions, of the Users, the Spaces and the Context [6].

Relying on concepts from cognitive science and in particular, a branch called "situated cognition", Gero says that we can build simulation systems that encode "first-person" as well as "third-person knowledge".

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3.4 Behavioral Knowledge and Cognition

According to Vernon [14], we can generally classify two different approaches to computing Cognition, having diverse positions on knowledge:

- On the one hand, the *Cognitivist* method aims at representing symbolic information processing. It takes a mostly static interpretation of knowledge, represented by symbol systems that refer bidirectionally to the physical reality external to the cognitive agent. This knowledge raises reasoning processes on the representations provided by the perceptual apparatus. As a consequence, it plans actions in order to achieve programmed goals. The Cognitivist approach to knowledge representation can be best characterized by the traditional *Perception-Reasoning-Action* cycle.
- On the other hand, the *Emergent Systems* approach takes a mainly dynamic or procedural view of knowledge and sees it as a collection of skills that understand the "how to do" things.

The "*cognitive agent*" is on a higher level, thus it depends on the agent, as well as on the space and context. Both the agent and its environment are developed in real-time, which is substantial for cognition and its emergence or appearance.

There is another crucial difference between the two paradigms:

- In the *Cognitivist* paradigm, it is mostly based on the designers' frame of reference. External designers, or knowledge engineers' observations, descriptions, and models are the basis for the configuration of perceptual capacities: namely what Gero [15] calls "third-person knowledge".
- The Emergent Systems paradigm is mainly based on the agents' frame of reference. The action space defines the perceptual space. The capacities are derived from a historical process of active and embodied growth, which is rooted in the extensive understanding of the cognitive agent within its environment. This includes Gero's "third-person knowledge" and ad-hoc, situation-generated, "first-person knowledge".

To conclude, in the *Emergent* paradigm, true cognition has to be developed in an agent-centered manner, meaning the Users interacting, learning, and co-developing with the Space and Context.

On the tracks of the two different paradigms here presented - oriented to computing behavioral knowledge and cognition of the actor in a context - in the following section 4, we illustrate a general framework for behavior simulation.

Compared to the existing design technologies both in research and practice, the innovation resides in the new methodology proposed for enriching the BIM model (IFC entities) with semantic values, oriented to the user's well-being. This research moves beyond static models to goal-directed behaviour simulations by adding semantic reasoning.

The research challenge - residing in the complexity of integrating semantics into BIM - is addressed by the methodology defined in the section 4, and by the implementation pipeline proposed in section 5, that is in an advanced experimental phase, integrating multiple technologies into a unified simulation model. We checked some crucial aspects of the feasibility of the software integration, but the workflow may require significant modifications to automate it in the existing tools.

4. A General Framework for Behavioral Simulation

The conceptual view of the next generation of integrated building performance frameworks that merge two (currently) disjoint worlds, the BIM and the Use Process systems, must have as a central reference point for analysis, the dynamic behavior of building occupants.

The quest of this research is to reflect on potential paths for engineering knowledge and understanding, by providing a BIM system (overcoming limitations of IFC standard structure) and other existing simulation tools (overcoming predefined rigid agents' patterns), the semantic information required to operate adaptively and achieve robust and innovative goal-directed behavior. The general framework, extending previous works [4, 5, 6], outlines a multilayer organization:

- 1st layer – Object-based for project data automation (BIM);
- 2nd layer – Ontology-based for semantic reasoning (IFC modular enhancement for inferences);
- 3rd layer – Cognitive-based for comparing goals and exploring consequences /side effects of design choices (Semantics Engines/Agents/).

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4.1 Use-Process Simulation Platform

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 at the instant T0,
- A *dynamic* component, able to perform the changing of the entity's state from the system status T0 to T1.

In recent years, agent-based modelling 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 interacting autonomously with the other users and the surrounding environment.

The Digital Construction Ontologies (DiCon) can be identified as the most comprehensive effort to include all the domains involved in construction, making use of existing ontologies, considering the BFO ISO/IEC 21838-2 standard as a base ontology [16]. Digital construction ontologies seek to encompass the pertinent entities and characteristics (including relationships and attributes) that can be referenced by people or systems in the oversight and implementation of construction or renovation projects. From the perspective of construction management (and only for this aim), Activity - a subclass of process - captures the intentional efforts of an Agent. An Agent can be a Person or an Organization, and can have Capabilities and assume Roles [17].

As discussed in previous sections, this kind of simulation approaches, such as the "narrative approach" doesn't allow for prediction, but rather pre-defined scenario visualization. According to Kalay [18] agent-based models have 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 space-context dependent decisions and behave interleaved.

The simulation platform here presented integrates two main modules:

- Use Process Knowledge, whose structure has been presented in previous papers [4, 5], linking, in a homogeneous computational environment, BIM to the 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.

We assume that Agents should be associated with AI resources, that reside not only in the users' Knowledge Bases but also opportunistically in other entities: Context, Product, intended as the organic relation between Spaces and Components, and Process ontologies. This association helps to decrease computational burdens and allows inference engines to perform cognitive, dynamic, rule-based reasoning.

This implies that it is necessary to extend the BIM model with more abstract semantic levels, for instance, in such a way as if Building components and Spaces are characterized not only by parameters related to environmental comfort or physical requirement but also characteristics of space-time functionality, linked to the Use Process entities. The proposed workflow includes the instantiation of the building process schema, defined by Process Analysts for representing the occupational activities, by means of structured Use Process Knowledge. A synthetic representation of a framework, oriented to reconcile discrepancies between the process-use analyses of "real" and "simulated" buildings, is illustrated in Fig.3.

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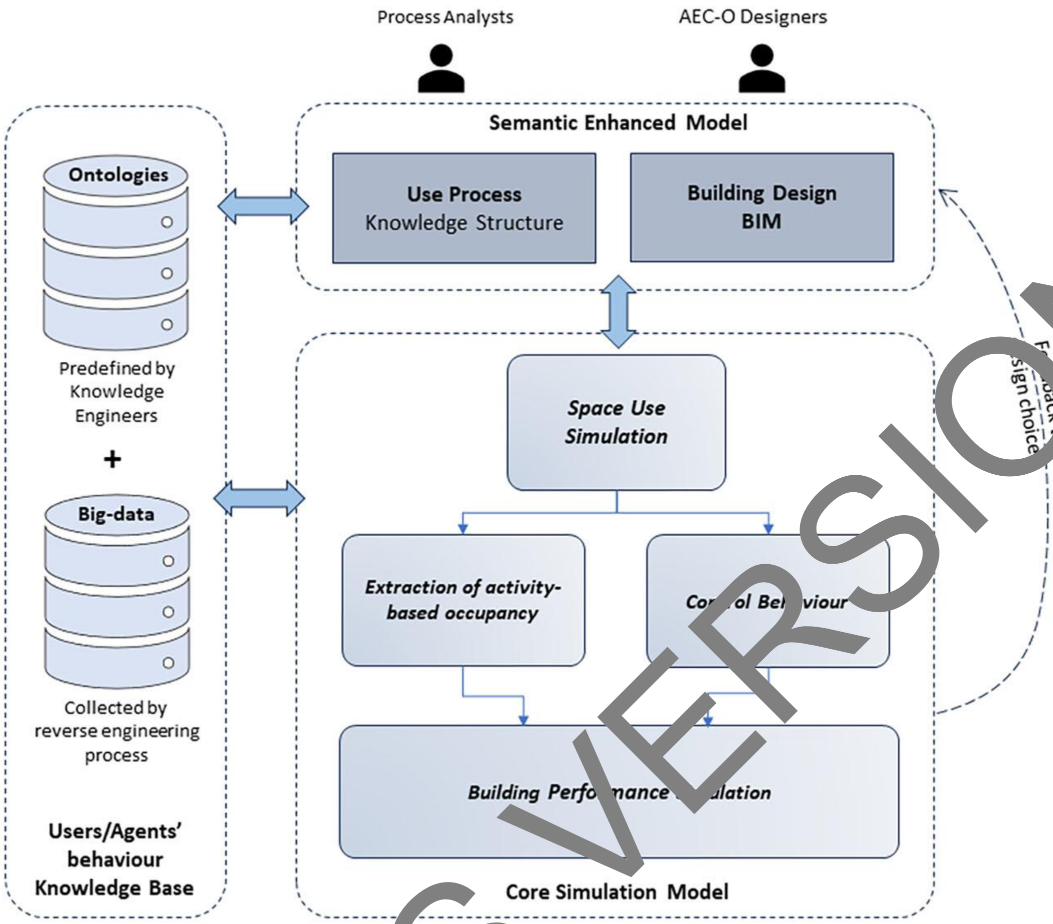

Figure 3 – A general framework for extending BIM to user-space behaviour simulation.

4.2 Methods for Collecting Formalized Knowledge

Due to sophisticated data collection technologies, occupant behavior modelling can rely on many different approaches, according to their objectives, such as agent-based modelling, statistical analysis, data mining techniques, stochastic process modelling, and other related methods [3].

To collect formalized knowledge related to users' profiles in order to model phenomenon and process simulations, the authors classify two main methodological categories.

– On one side, more traditionally, *knowledge-based techniques*: designers and knowledge engineers identify and model use-process requirements based on *a priori* operational needs – e.g. Use Process Knowledge structures [4] among other research in the ontology AECO domain [19, 20, 21, 22, 23] –. Experts also work on defining space users' Personality Typologies by means of structured surveys for outlining differences in the same classes of users approaching the same activities (preferences, value orientation, expectancies, attitudes, etc.).

– On the other side, *(big-)data-based approaches* (i.e. Bayesian networks, decision trees, etc.): the knowledge source originates by a sort of reverse engineering process, capturing data, information and knowledge from real world monitoring, by means of different media technologies (temperature detector, camera, RFID, Internet of Things, etc.) [24].

The implementation pipeline for capturing information and assigning a structured meaning, according to the currently available technologies, including recent advances in AI, can be developed by following this process:

REALITY -> BIG DATA COLLECTION -> DATA DRIVEN PROCESSING ->
ONTOLOGY RECOGNITION -> ONTOLOGY POPULATION -> COMPUTING COGNITION.

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Once collected (by big data approaches) and formalized (by ontology-based approaches), Use Process knowledge can be computed to implement advanced process simulations.

We consider that the two mentioned categories are both valid, complementary, and they are not alternatives. 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. Current hybrid approaches such as Gomez-Romero et al. [25] 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 At the same time, it could help overcome current limitations in scenarios with several actors, providing semantics to social activities, user identification (according to behavior semantics), and so forth.

As a concluding remark, we argue that in next generation of users/context behavior simulation models, a hybrid approach for computational technique should be adopted, 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.

It is also important to remark that if we use simulations in a virtual world to predict future events of the real world, we have to reliably represent it, but not be limited by the real-world rules. So, while in the real world only people have the capabilities to think, evaluate the environment and control their behavior, in the virtual digital world this task can be assigned to all the entities populating the model, representing both, physical or abstract objects, regarding Product, Users, Context and their interaction. This observation is open to further investigation for including and making explicit the unexplored, potential context capabilities together with users' adaptations, and vice-versa, the potential context adaptation together with users' capabilities.

5. Implementation Pipeline and Early Results Discussion

This paper belongs to larger-scale research by the authors, grounded on several progressive refinement studies about the general conceptual framework here discussed, including implementation of selected key components tested on specific case studies by adopting and customising innovative technologies.

Methodologically, the investigation proceeds according to the following steps:

- On one side, more traditionally, *knowledge-based techniques*: designers/ knowledge engineers identifies and model use-process requirements based on 'a priori' operational needs – e.g. Use Process Knowledge structures [4] among others researches in ontology AECO domain [19, 20, 21, 22, 23] –. Experts also work on defining space users' Personality Typologies by means of structured surveys for outlining differences in the same classes of users approaching the same activities (preferences, value orientation, expectancies, attitudes, etc.).
- Study of the knowledge domain related to the (re-)use of built heritage and the identification of the knowledge to be modelled for the purpose of the platform;
- Definition of a digital Knowledge-based Model for the formalization of the knowledge related to the artifact and its intended use and users;
- Formalization of that digital knowledge by activating a collaboration between experts in AECO design and knowledge engineering fields;
- Selection and definition of simulative approaches (algorithm, heuristic, PL, etc.) and models for the interpretation and prediction of the use processes together with the related building performances (main focus on space layout functionality);
- Integration of the Building Knowledge Model environment and the Simulations environment within the platform;
- Selection of some case studies and experimental application of the platform (to be performed recursively for the model calibration);
- Verification, validation and critical analysis of the platform and its functioning.

For implementing this theoretical model, we are using ontologies plus agents (upper ontology level) in order to model the use process entities, physical or abstract, and their space-time relationships structured by means of M-P-R [4] *Meanings*, *Properties* (defining their state) and *Rules* (relations, reasoning rules, consistency, best practices).

Rule-based analysis, checking, evaluation and control of concepts associated with specific entities are performed by means of inferential engine demons, with deductive "If-Then" type procedures. A system of engines works on a

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deductive layer overlapped at the actual BIM level, allowing the designers to use coherently different levels of abstraction.

The implementation steps are here summarized:

1. Representing the Design Knowledge regarding Use Process *Ontology*.
   Use Process Ontology - structured by means of Activities, Actions, Rationale and Events starting from basic ergonomic functions up to more complex procedures - is implemented by Protégé ontology editor and expressed in OWL2 language [2, 3, 10].
2. Connecting Use Process and Building Ontologies with actual BIM/IFC entities.
   It involves the following steps:
   - the database containing objects (and their properties) that make up the existing (or just designed) building, modelled in Revit, is exported in Access format, using the DBLink plug-in;
   - the ontology formalized in Protégé OWL2 is converted into a MySQL open-source database. This conversion produces an unstructured database, but rather made up of strings in a single-table format;
   - the ontological database is then parsed by using a tool previously developed by the research group [6], in order to identify the strings regarding instances related to Spaces and Components of the building, the properties and the values assigned to them in addition to the Classes they belong to. This task can be facilitated, only for BIM families, by using the transcription of IFC in OWL [23];
   - the instances - with their properties - corresponding in the two databases (Protégé, Revit) are then manually mapped.
3. Developing the platform for processing BIM+ Ontologies within a Narrative environment.

The platform implementation constitutes a complex task, actually still in an experimentation and validation phase, that has been conceived utilizing the Unity 3D game engine (it can also consider BPM, Virtools, etc.), with agents' behavioral rules, activity execution protocols, and narrative management systems.

The building and its various space-components entities, modelled using BIM software (Autodesk Revit), have been subsequently exported to the game engine platform (Unity for Autodesk Revit application), where the entities are enhanced with Behavioral Rules.

In this case, these testing rules are formalized using ad hoc scripts in the game engine, actually coded in C, based on their typology, and intended as a functional program. The set of behavioral rules has been assigned to the different "smart" space-components of the artefact in order to allow to overcome the static role. They do not actually control behavior, but rather assess the variation of specific parameters related to the activity-based function of the element. For instance, the check of layout versus a business program schedule, or if the number and type of furniture and equipment are appropriate for the scheduled activity with the effective number of users in the spaces, or testing the performance of building components designed (slabs for loads, doors for circulation, internal walls for acoustics, etc.).

While the simulation is running, the Space-Components entities, equipped with AI resources similarly to the autonomous agents and the pre-defined activities ones, measure the effects of users' behaviour on them (and on their intended performance), providing immediate feedbacks to the designer.

To summarize, the integration of three layers into current BIM workflows has been only partially implemented: as described we checked some crucial aspects of the software integration feasibility, but the workflow may require significant modifications to automate it in the existing tools: at present, this work can count on a limited but representative number of building product/process entities.

Future implementation work regards the software facility to import behavior rules written in the ontology language into the game engine environment to apply them directly to the population of Space-Components entities, overcoming ad hoc scripts in C. At the moment, authors noted that Web Ontology Language 2 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) or SPARQL Inference Notation (SPIN), 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 the 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 (calculation, comparisons, string and time).

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6. Conclusions

Currently, in buildings behavior assessment, we assist to a strong leading use of IFC standard in the design process models, although there is a significant absence of design semantics, methodology and best practices due to its centralized structure and language (Express) – inherited from the automotive engineering industry.

To overcome these limitations, many researchers are implementing new *ad hoc* ontologies, but we must be aware that the diverse efforts need to converge, marking a route towards a common and broad use of interoperable ontologies in future constructions.

Moreover, despite the great advances produced in the last decade, the complexity and the quantity of possible intricate activities, the temporal interdependences among actions, the relevance of the semantics associated with behavior, and the existence and interaction of several users in the same environment/context, make learning and recognition of human behavior an open problem, and bring up clear, relevant challenges in present research both in academia and in the production sector.

The research framework outlined in this paper starts from reviewing theoretical bases of occupancy analysis - Users / Context profiling and reciprocal cognitive interaction - in order to address a methodology to collect and formalize Behavioral Knowledge.

The simulation model here presented is divided into two main modules:

- *Use Process Knowledge* linking, in a homogeneous computational environment, BIM to higher-level semantics, defined and implemented by authors;
- *Simulation engines* to perform and visualize the effects of the model status change.

A general framework integrating multiple technologies into a unified simulation model for extending BIM for simulating users' behavior has been illustrated: it is based on an innovative three-layer computational architecture: Object-based BIM automation (for physical data representation); Ontology-based semantic reasoning (to add structured knowledge); Cognitive-based simulation (AI-driven behavioral adaptation).

An original hybrid approach for computational techniques combining (big) data-driven algorithms with ontology-based context reasoning has been investigated from the point of view of an AECO design knowledge operator. As ontological reasoning can be computationally expensive, this type of combination has been shown to be a promising path for further research in order to achieve both 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 specific case.

At present, although it is a well-structured and solid framework, the integration of three layers into current BIM workflows has been only partially implemented: we checked some crucial aspects of the software integration feasibility, but the workflow may require significant modifications to automate it in the existing tools: this work can count on a limited but representative number of building product/process entities formalized by means of current ontology editing systems, in order to be used for automatic design reasoning, using the large family of ready-built inference engines and information extraction tools.

Further investigation is oriented to include, making explicit in the design the general model, the unexplored potential context capabilities together with users' adaptations, and vice-versa, potential context adaptation together with users' capabilities.

Among the outcomes of the framework, emerges the potential offered by the dynamic and semantically-specific representation, along with Inference and Simulation Engines, to predict human behaviour, so coherent/favorable situations will be evaluated by means of a set of constraints, and will be highlighted and managed in real time.

At the same time, it will allow actors to assess alternatives, more consciously reflecting on the consequences of their intentions. In this way, the impact of a networked ontology makes designers more aware of overall problems and allows them to operate more participative and shared choices.

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8. Authors Contributions

Conceptualization – A.T., A.F.; Project Administration – A.T., P.F.; Methodology – A.T., A.F. P.F.; Software Coding – A.F., A.T., P.F.; Data Curation – A.T., A.F., P.F.; Writing and Validation – A.T., P.F.; Investigation – A.T., A.F., P.F.; Funding Acquisition – P.F., A.T.

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