A framework for ontology-based design assessment for human behaviour during fire evacuation

Conference Paper · July 2017

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Abstract. The current procedures in assessing fire performance designs are costly and inefficient, as they require the preparation and analysis of several scenario models, which may change at every design iteration. To address this, this paper presents a way to leverage BIM model data using OWL ontology tools to integrate, automate and provide feedback to the design decision-making process. The paper introduces methodologies from research which are relevant to the presented concept, then expands on a problem identification section, arguing why crowd simulation analysis might also benefit the ontology-based approach. The core emphasis of the paper is the framework required to achieve the process where ontology rules, reasoning and inference are leveraged from existing IFC models, with minimal user input. The framework consists of several components which are described independently, based on a system currently under development. A use case presents the practical flow of the process and some of its requirements and limitations.

1. Introduction

With the gradual increase of interoperable tools and the proliferation of the IFC format, BIM centric design and management has led to the use of BIM and IFC as a means to assess code-compliance in performance-based design (Eastman et al. 2009). However, most of the tools and methods are less suitable in performance-based design situations, where the regulation process needs to include modelling assumptions such as data input and their sources, as well as the analysis results. Conventionally, these factors are usually at the discretion of the designer, based on personal and professional judgement and knowledge. In this sense, we aim to explore how more advanced information formats which support basic semantic reasoning can fill this gap, by adopting ontologies as tools to integrate information, automate the processes and provide adequate feedback. Several studies have already adopted similar methodologies when considering either rules checking or other building performance design criteria, which will be presented and discussed, along with the reasons we believe ontologies can leverage BIM information.

This paper aims to identify how semantic web applications can be used to integrate and automate the performance based design for safe fire evacuation. Based on this, the methodology we adopted looks to: a) identify the problem with fire escape design analysis and rules checking and b) propose a framework which describes the process of using semantic linked data and reasoning for performance based design of human behaviour analysis. A short use case example is presented at the end.

2. Related work

Pauwels et al. 2011 is one of the pilot studies investigating the capabilities of semantic web rule checking, applied to acoustic building design. They state that limitations in the IFC schema expressivity of concepts are overcome by an ontology approach. Another pilot study on using ontology tools is Scherer and Schapke 2011, which describes a framework for using ontologies as a means of integration on the project level, which can include multiple models and processes. Such approaches allow the rule checking process to go beyond the schema scope, thus allowing for more flexible model view definitions, which is crucial in including non-traditional design analysis under the BIM umbrella.

Venugopal et al. 2015 investigated the current state of exiting Model View Definitions (MVDs) and concluded that the processes behind them are inefficient and not future-proof as the industry expands its use of the IFC. The authors consider ontology representations of the IFC schema to allow for a flexible and more robust backbone for interoperability requirements. The computer-interpretable features of ontologies allow for validation methods and easier extensibility of other disciplines into the design process. Their ability to represent knowledge is better suited for the underlying BIM models, as is more robust than the IFC schema, while also being a good interoperability tool (Venugopal et al. 2015). There have been several applications of ontology data linking for specific applications in the AEC sector, mainly focused on energy, cost and risk analysis, but limited focus on human behaviour design analysis.

Buildings are designed to achieve minimum levels of safety regarding fire design. This usually comes down to prescribed regulations, which vary by region. However, prescriptive regulation design can restrict design in other fields, and thus simulation tools for human behaviour or fire fluid mechanics are used to assess building performance, where they are not met. Over the last decades, dozens of tools capable to simulate human behaviour in buildings have emerged, each with its own benefits and limitations, as reviewed more recently by Ronchi and Nilsson 2013.

Regarding fire design, there have been several attempts to explore integration of fire tools with BIM (Wang et al. 2015, Wang and Wainer 2015), with a small number aimed at regulation checking standardisation (Dimyadi et al. 2016), and even fewer aimed at performance design review. In most cases these attempts use IFC data in a static way, and mostly rely on the 3D information, making the process inefficient and lacking in interoperability. Wang and Wainer 2015 developed a system to provide crowd simulation as a service, integrated with BIM tools to some degree using IFC. This study however fails to address the complexities regarding information input specific to occupant data apart from geometric building data, or how simulation results can relate to existing BIM models and its object components.

Dimyadi et al. 2016 is one of the first comprehensive attempts to include fire rules in checking applications by importing IFC models. This is a more traditional approach in terms of rule-checking environments, expressing design rules in code format and using Regulatory Knowledge Models (RKMs). However, most of these implementations were initially intended for prescribed regulations checking, rather than for performance design. Dimyadi et al. 2015 explored the potential to link the above-mentioned RMKs to ontology concepts, for a more efficient compliance audit model, in order to give it more interoperability with other tools, while also being seen as more suitable for performance assessment, due to increased expressivity. However, there have been no actual implementations of such methodologies to the best of our knowledge, so far.

3. Problem identification

Building design is becoming increasingly complex in terms of process due to the need for optimised designs in multiple disciplines, project size or complex architecture. This puts a lot of pressure on designers to deliver safe, optimized and aesthetically pleasing buildings, in a limited amount of time. As the ability to improve or change a design diminishes over time during a project, design decision making must be precise and based on adequate scenario analysis in order to achieve the best results. Thus, building performance design audit domains need to be more efficient and collaborative across multiple disciplines, a gap which could solved automating several processes involved.

With design analysis tools and the proliferation of BIM technologies and processes, the potential to deliver better designs has improved. BIM not only improves the process, but it also offers new ways to manage and use data in a more integrated way. According to a recent study on industry and academic trends on BIM related subjects (Leite et al. 2016), some of the biggest challenges under consideration are the processes of simulating and predicting building behaviour and verification and validation of the simulation output. The authors also note that there are virtually no standard data sets or methods for predicting human behaviour in terms of energy usage or building usage in general. This increases the need to predict occupant behaviour, from the earliest design stages, across all fields.

Interoperability and integration of structured data sit at the core of BIM. The IFC format has been developed over the last 20 years in the hopes of solving this issue. While IFC has become a strong base for carrying out BIM level 2 projects, it cannot include every aspect of the building design across its lifecycle. Many studies in the area of costs or energy analysis try to work directly on the IFC schema and several IFC schema extensions have been proposed, including for fire safety models (Dimyadi et al. 2016), limited however to prescriptive design checking.

When considering the act of creating a specific scenario for analysis, there are several factors and input information channels which contribute to the final results, including: building layout and geometry data, predicted building occupant behaviour profiles, design guides and regulations, as well as user input preferences. There is a need to define in what manner these factors contribute to the process, and how they are interrelated within the scope of automation.

Out of some tools able to integrate with BIM models, like Wang et al. 2015 via different geometry imports, or Wang and Wainer 2015 through the use of IFC, information importing is restricted to the building geometry, whereas simulation scenario contextual information is usually not available and hard to express programmatically. This needs to be provided by specialists via manual input.

Crowd simulation analysis usually involves several iterations for two different reasons: the probabilistic nature of crowd simulation tools and the variety of scenarios to be assumed by designers, where different layouts or building capacities are evaluated. This can be a very time consuming process, and because of this, the lack of continued and thorough analysis might leave the building design underperforming. In addition to their intrinsic limitations at simulating realistic behaviours, simulation tools require a lot of assumptions which develop into very specific scenarios. In order to move the domain towards automation, representing such assumptions programmatically is required.

Ontology tools enable us to capture expert and regulations knowledge directly into our computational systems, allowing us to leverage information and cloud computing processing, where crowd simulation analysis can become an integrated service towards the BIM design and decision making processes.

Since ontologies are regarded as a good interoperability tool, we believe they have the potential to integrate the whole process and deliver faster scenario generation and improved analysis. Furthermore, from the perspective of the iBIM paradigm (or level 3 BIM), web semantic integration appears to be the next step. This suggests that ontologies are the means to achieve

BIM level 3, allowing data integration across several domains, along with the integration of Internet of Things (IoT), and other structured data formats available across the web.

In light of the above, we see ontologies as the only tool able to meet our needs in the way forward for integrated and automatic tools, for the time being.

4. Methodology and hypothesis of overall research

The hypothesis of our research is that current BIM technologies and processes can be leveraged to enable more automatic and integrated performance designs regarding human behaviour analysis in buildings, making the process more efficient and allowing knowledge feedback into the design stage for review and analysis. The methodology of the research involves several steps: integration of Crowd Simulation Models (CSM) with IFC models in OWL format, representation of simulation scenario from design rules, description of the framework for a fully functioning system, validation and testing.

This paper presents part of the overall research, the architecture of the system along with sample testing scenarios.

5. A framework for ontology-based fire escape analysis

The process of the proposed concept, described in Figure 1, showcases an automated process where crowd simulation scenarios are generated automatically, according to design input and ontology rules and reasoning. Feedback to designers is provided by ontology reasoning and interfaces, which considers input variables and simulation results. In order to achieve such a process, there are component requirements. The framework for such a system is best described by its components and their functionality in the entire process:

1) Input data models – provides all relevant input from building model information, user preferences and design constraints; any other additional data such as sensor data or design variable tables, depending on the context, can be included;
2) Ontology core – framework component which stores all the required information in RDF format, including representations of software components, model data, alignment models and reasoning rules;
3) Output models – refers to two types of output modes. The first is the generated analysis scenarios to be run and their respective additional generated data used for analysis. The second is the output provided by the ontology reasoning for design feedback;
4) Interfacing plug-ins - refers to the customised interfaces which are used for providing a user-friendly experience.

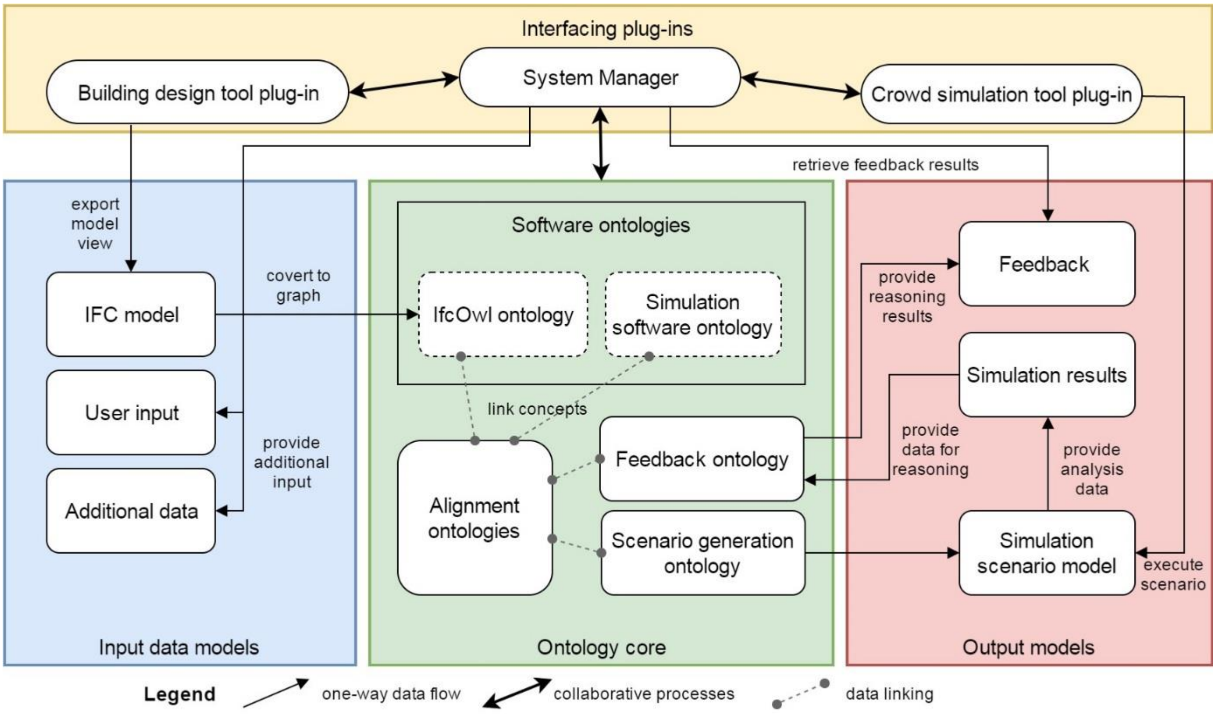

Figure 1: Framework components categories by their functionalities and their interaction

Each of the main framework components has specific roles to fulfil, depending on the stage of the process:

I. Scenario generation automation stage – all required inputs are aggregated into a valid crowd simulation scenario, which is then executed for analysis;
II. Scenario analysis and feedback stage – executed scenario data is queried, ontology reasoning is used to assess design rules or objectives, which provides feedback to users.

5.1 Input data models

The input models refer to several independent elements, which provide the required input for the entire process to work, as follows:

- IFC building model – a view of the IFC model as exported by a proprietary BIM platform. A full view is not required, but a specific MVD for crowd simulation analysis is not yet released, as such a normal coordination view is sufficient as it provides full geometry data as well as all other relevant annotation objects. The IFC model can store customised textual and numeric properties which could represent the design requirements, such as space occupancy numbers, densities or classification of spaces. This is probably the most efficient method to ensure a full model view for this purpose, as object data is easily mapped to each object instance through the IFC semantics, and thus requires less reasoning by the ontologies.

- User input – in addition to the specific data requirements present in the IFC model, user input needs to complement the data by adding specific contextual information, such as types of scenarios, objectives of the analysis process and including other sources of information if the IFC model only provides partial data (e.g. occupant densities)

- Additional information – this refers to any other contextual or data input channels, which vary based on the BIM lifecycle stage. For example, designers will use design values from tables and classification systems (such as Uniclass), but building managers might prefer to use historical or sensor data.

5.2 Ontology core

The ontology core is the aggregation of the semantic representations of tools and processes used in order to achieve the proposed concept, by leveraging the input data via reasoning, and also providing interoperability to the entire process. To ensure a functional system and convenient maintenance, it is recommended to adopt a segregated approach of the core ontologies used, which are then linked via alignment ontologies. The types of ontologies required are:

- Software ontologies – refer to the ontology representations of the different BIM tools which are part of the system. In this case, the IFC building model, represented in the IfcOwl ontology, and the MassMotion (Oasys Limited 2017) model, the third-party crowd simulation tool chosen, and its respective ontology. These ontologies represent the inner structure of the software model objects, which are described in an object-oriented way. Since there is no standard for crowd simulation, unlike the IFC, this means an ontological representation of the software is necessary at the moment.
- Scenario generation ontologies– at its core, this part of the system deals with automation of model data. In the crowd simulation domain, it needs to define concepts such as: spaces and their types (inhabited, uninhabited, fire refuge, etc.), occupants and their behaviour, as well as other contextual knowledge like type of scenario (e.g. at full or partial building capacity). It consists of many rules able to reason according to input: what spaces are used and how, which parts of the building are populated by agents and their number, and where the input data is coming from. A scenario generation ontology needs to be precise and comprehensive in representing design knowledge and intent. It can become a mixture of best practices, in terms of knowledge representation, but it should also be able to encompass concepts related to user input preferences. For the approach adopted here, we have chosen to represent design knowledge from UK British Standards codes of practice, namely BSI PD 7974 2004, part-6, when using crowd simulation tools. While the codes can sometimes be vague or allow for designer lee way, it is necessary to represent the choices available to the users as well. This allows more variety of scenarios and brings more complexity and potentially more relevant information to the results feedback stage.
- Feedback ontologies – similar to the previous, the feedback ontologies represents design knowledge, but the evaluation and analysis perspective. They need to encapsulate various reasoning rules, which are in line with analysis objectives. These may relate to evacuation times, bottleneck points, agent behaviour, assemblies of objects which influence results. Like with the previous, to ensure relevant and precise knowledge feedback, input data, user preferences & objectives and software limitations should ideally be taken into consideration when representing this field.
- Alignment ontologies – this provides the interoperability of all the different knowledge and application domains involved, mapping data across the different ontologies mentioned above. The alignment ontology can also resemble the role of an MVD data transfer protocol. The main difference however, is that all the data in the other models can still be present, and with the correct mappings, accessible for future extensions.

The approach adopted in our research was to host a series of different ontologies on a commercial RDF server, namely Stardog (Stardog Union 2017), which enables easy access to the database via HTTP protocols using java APIs.

5.3 Output models

There are two types of output, corresponding to each process stage mentioned above:

- Simulation scenario model – represents the output of the automation process, consisting of a specific scenario, which is then executed to generate results;
- Simulation results – refers to the additional data provided by the crowd analysis software, after executing scenarios. The output data depends on the software tools used. In our developments, data is provided in SQL format. The alignment and feedback ontologies need to access only the required data, thus separate queries to the data were implemented to integrate the SQL.
- Feedback rules output – refers to the output provided by ontology rules execution and reasoning, as mentioned in 5.2. The reasoning is handled by the feedback ontology, but querying for the answers should be handled by the interfacing software.

5.4 Interfacing plug-ins

While the previous components collaborate in the background and manipulate data, the interface plug-ins have the role of managing the querying of the ontology embedded knowledge according to user preferences. The secondary role of the interfaces is to restrict the ontology reasoning scope and complement any limitations which ontology rules might not be able to perform, such as data format conversions, or the creation of new ontology individuals. The interface is vital to conducting a logical process of the underlying services, and act as connectors to the entire system.

5.5 Multi-layered architecture system

In order to achieve a federated modelling approach, we have adopted a multi-layer architecture for our developed system, as described in the figure below.

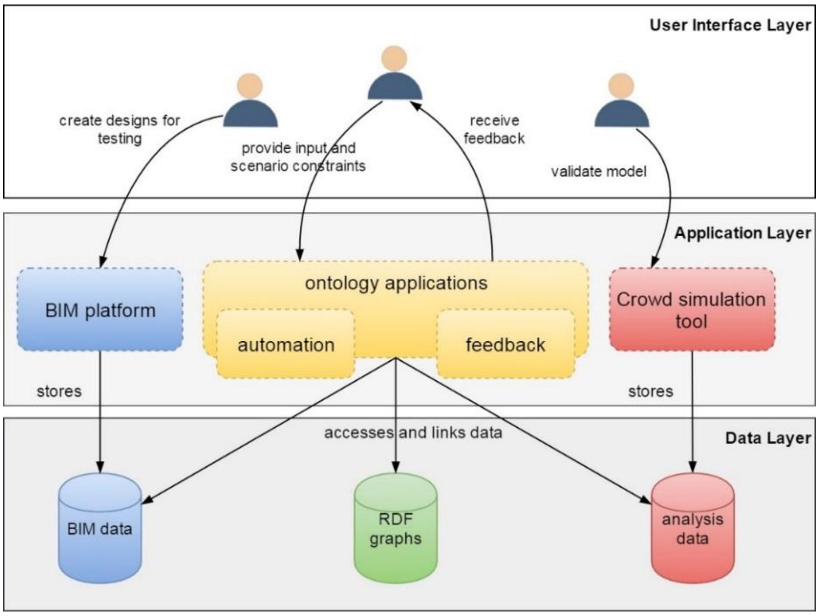

Figure 2: System architecture used in research, its layers and basic components

The main layers have the following functionalities:

1. Data Layer – stores all the data in different federated databases, including BIM models, RDF graphs which contain all the mentioned ontologies and SQL data from the analysis software.
2. Application Layer – while the different BIM applications and tools to not need to collaborate explicitly, collaboration is achieved via the ontology applications. They manage the performance review process, and have access to all the data in the lower layer. The BIM platform and crowd simulation tools are both provides or data in this case.
3. User Interface Layer – consists of all the separate interfacing plug-ins, which allow user input and feedback of the underlying layers.

6. Use case example

The current development of the system consists of a main Java application which interacts with the Stardog RDF servers. The IFC models are initially created in Autodesk Revit, and then converted to IfcOwl format. The ontologies and the rules were implemented using the Protégé software. Partial tests were carried out during the software implementation, and the ontologies were constantly checked using several reasoners.

When generating the scenarios, for automated crowd model generation, all the required data was provided in the IFC model, such as roles of space and their occupancies. Building components from the IFC model were directly mapped to the MassMotion ontology, thus any IFC model individual that has a MassMotion corresponding type, is also a MassMotion individual. As such, the *first step* involved selecting the required information from the IfcOwl model, as a reasoning query in SPARQL:

```
PREFIX mmOnto:  <http://icompe.engineering.cf.ac.uk/MassMotionOntology#>
PREFIX express: <http://purl.org/voc/express#>
PREFIX ifcowl:  <http://www.buildingsmart-tech.org/ifcOWL/IFC2X3_TC1#>
SELECT DISTINCT ?ifcId
WHERE {
  ?instance rdf:type ?class .
  ?instance ifcowl:globalId_IfcRoot ?guid express:hasString ?ifcId .
FILTER (?class = mmOnto:Actor) }
```

In the case above, "mmOnto:Actor" refers to any objects which have a geometric representation in MassMotion models, such as: floors, walls, spaces, stairs, etc. The query above is the first step in filtering the information required, which replaces the need to use a specific MVD for this purpose, as it already imbedded into the alignment ontology.

The *second step* involved generating the geometry of the objects from the IFC format (also now stored in the ontology model) to the MassMotion representation in XML. We have developed a software which queries the IfcOwl model from the servers and reconstructs the geometry of every object into MassMotion format. This was necessary due to a lack of an existing API for the crowd simulation software to date. Knowledge of the structure of the IFC schema and the crowd software geometry is required to perform this step. The IFC schema and its Owl representation are object-oriented, thus it usually generated lengthy queries to the IfcOwl model, to retrieve basic datatypes, such as strings and integer values. This can become very costly in terms of reasoning time, if the SPARQL query is long and if it contains vague triples, or multiple UNION operation of results. To optimise this, the geometry was queried without any reasoning flags, while storing in memory the global "IfcId" of the objects in question, which was used to identify individuals across multiple queries.

Unlike the geometry, contextual information present in the IFC (such as types of space, occupant number) varies with the situation. As such it was expressed in SWRL rules and reasoning was used to obtain it for scenario by scenario basis. For example, the SWRL rule below, seeks to identify which space is inhabited, based on its corresponding occupancy number:

```
Space(?space) ^ hasAgentNumber(?space, ?agentNumber) ^ hasInteger(?agentNumber,
?value) ^ swrlb:greaterThan(?value, 0) -> InhabitedSpace(?space)
```

These sort of rules can become very useful in finding inferences from data and semantics present in the IFC model. However, due to the expressivity of the SWRL syntax, it becomes quite challenging to express certain rules. For example, considering the rule above, if a "Space" type individual meets the requirements, it automatically becomes an "InhabitedSpace" type as a sub-class of "Space", but we cannot state in the same rule what happens if the result is false. As such, the contrary rule needs to be implemented to classify a space as "UninhabitedSpace" type:

```
Space(?space) ^ hasAgentNumber(?space, ?agentNumber) ^ hasInteger(?agentNumber,
?value) ^ swrlb:equal(?value, 0) -> UninhabitedSpace(?space)
```

It's important to distinguish between "inhabited" and "uninhabited" types of spaces correctly in order to make the correct scenario assumptions. For example, crowd simulations guidelines (PD 7974 2004) usually do not consider circulation spaces as inhabited, which is not possible to distinguish from the IFC model alone, without some ontology reasoning on top. We have implemented several rules in establishing this, according to specified occupant numbers, as expressed above, or according to Uniclass codes, where each space code corresponds to either of the two categories. Unfortunately, due to the Open-World Assumption (OWA) which OWL adheres to, there is no way to check if the space is inhabited or uninhabited if the required information to assess it is not present in the ontology. To overcome this, the ontology representation needs to be tested in multiple scenarios.

After the scenario automation stage, the *third step* involved running the MassMotion simulation model. The model contained all the geometry, as specified in the alignment process, as well as all the other contextual data provided by the data and ontology reasoning. These could be considered the initial parameters and assumptions of the simulation input. The simulation tool executed the scenario, providing a database in SQL of raw data.

For the *fourth step*, the data was queried according to the feedback ontology requirements. For example, a parameter of interest to designers considered was the total travel time of agents, which was looked up the SQL database and transformed as an ontology individual in the RDF graphs. A rule was then applied to check the results against user requirements:

```
TravelTime(?time) ^ InputTravelTime(?requiredTime) ^ swrlb:lessThan(?requiredTime,
?time) -> AcceptableTravelTime(?time)
```

The last step involved querying the RDF graphs for specific feedback, which is handled by the interface. As imbedded rules and inferences are present in the ontologies, data about specific individuals needs to be selected using specific SPAQRL queries and the results need to be presented in a user-friendly format. The last two steps of the development described are still a work in progress.

7. Summary

Current procedures for fire escape performance design are hard to assess and require significant input from designers, making the entire process costly and inefficient. In this paper we have presented a way to leverage BIM model data to provide integration of several tools, automation of data and ways to provide relevant feedback to designers. Based on a short literature review of similar concepts, the use of semantic linked data paradigm seems to show promise in complementing the IFC schema and integrating multiple design knowledge domains. A short problem identification raised the most important factors which might be beneficial for a performance based human behaviour analysis design case.

The framework for using crowd simulation analysis is dependent on a correct ontological representation of the tools, design regulations, user input and simulation results. Thus we have suggested a modular approach, where every component and its ontology representation are individually implemented, and all common concepts are mapped via an alignment ontology. The framework presented is based on our experience with implementing a similar system in practice, according to the described architecture.

The use case scenario provided shows a few simple examples of the ontology linking, reasoning and rules which are used as part of our overall research. The scenario showcases a few of the steps in the process of using ontology tools for integration, automation and feedback, along with some limitations of the ontology approach.

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