KNOWLEDGE-BASED ENGINEERING APPLICATIONS FOR SUPPORTING THE DESIGN OF PRECAST CONCRETE FACADE PANELS

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Abstract

Precast concrete facade panels, despite guaranteeing higher environmental performances, quality and quicker installation, are still designed starting from a conceptual, relatively constraint-free solution, in which details are included as the design develops. This traditional approach does not reduce risks in decision making, but rather, it increases the likelihood of devising a solution which is difficult to manufacture and/or unable to meet performance requirements, thus leading to inefficient use of time and human resources. This paper illustrates how a specific digital, knowledge-based engineering (KBE) application can support the design of single-leaf, non-loadbearing precast concrete panels. The application includes knowledge about preferred design and manufacturing constraints, and supply chain availability of a specific facade manufacturer. The result of this study is a digital application that informs design teams about the "tenderability" of the chosen solution, its approximate costs and expected performance. Future work will include additional functionalities, the development of specific metrics for assessing the impact in real-world projects and subsequent validation.

Keywords: Early design phases, Product architecture, Design for X (DfX), Constraint modelling, Visualisation

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1 INTRODUCTION

The construction sector has not experienced growth in productivity levels in the last twenty years, such as those seen in the manufacturing sector (McKinsey & Company, 2015). During the same time span, the share of construction on the overall greenhouse gas emissions has increased steadily (United Nations Environment Programme, 2009). Many countries are also facing an increase in population due to improving socio-economic conditions, thus requiring more affordable and comfortable housing, especially in densely-inhabited, urban areas.

Building façades play a crucial role in determining the optimal trade-off between initial and operational key indicators, such as building cost and environmental impact (Jin and Overend, 2014). Prefabricated precast concrete panels provide a solution in which a higher initial cost can be spread over a longer time span, while guaranteeing excellent thermal and acoustic performances. These panels also allow quicker installation and better control on quality.

The main challenge in delivering these products arises when they are designed without considering how they will be manufactured. Designers often have little or no access to a fundamental source of knowledge to support their design intent, especially during early-design stages, thus increasing the risk of devising a non-manufacturable solution. A shift towards a Design for Manufacturing and Assembly (DFMA) is therefore essential.

The aim of this paper is to introduce a digital, knowledge-based tool for supporting early-stage design by informing designers about a specific façade subcontractor's manufacturing capabilities. The tool therefore will function as a design tool that provides guidance for avoiding unrealistic designs and to inform designers how their choice affect key performance indicators. After a background overview in Section 2, the adopted methodology is shown in Section 3. Section 4 will describe the tool development and the results on a specific case-study, whereas Section 5 will conclude with final remarks and future work.

2 BACKGROUND

2.1 The design process of building façades

The design process of a façade follows a highly interdisciplinary and coupled activity where a large number of stakeholders share different views and priorities. In this scenario, the façade consultant mediates between different design streams and endeavours to devise the most economical and effective solution that meets a specific set of constraints and performance requirements.

There are different procurement routes in delivering façades, each one following the usual conceptual / developed / detailed workflow. More traditional forms of procurement appoint the design team for developing a detailed solution that will form part the documentation for the tender, thus increasing the level of competitiveness between potential façade sub-contractors. Other methods, such as the Design and Build (RIBA, 2013), appoint a general contractor earlier in the process, therefore allowing the design to be more aligned with the actual construction stage.

Regardless of the procurement route, late-design adjustments, which sometimes happen even during the construction stage, require large efforts in terms of use of resources and can cause severe contractual problems and cost implications. Both design and manufacturability issues can be encountered (Kassem and Mitchell, 2015), and the capability to correctly interpret early-stage design with respect to manufacturing constraint has been proven to be the main challenge in facade design (Voss and Overend, 2012). The use of dedicated software platforms with embedded manufacturing knowledge of main constraints that inform designers in advance is seen as a potential solution (Henriksen et al., 2016), although academic efforts and industrial applications in the area of digitalising knowledge about façades are still limited. Some see Building Information Modelling (BIM) as a possible solution to this problem. BIM is a standardised form of digital information exchange across stakeholders that stores information about geometrical and physical attributes of buildings and building products. The lack of embedded knowledge in BIM applications for façades, however, makes it difficult to interpret design as a complex network of interwoven performance requirements and constraints.

2.2 Knowledge-Based Engineering

The aerospace, automotive and shipbuilding industries adopt Knowledge-Based Engineering systems to develop specific applications that deal with the interdisciplinarity of their design processes and the need for automation. These applications usually merge specific programming languages and a 3D modeller. Central to KBE applications is the so-called "Product Model", the digitalised version of the final product that includes both physical components and associated design and manufacturing knowledge. A KBE application requires the user to provide a set of inputs that are elaborated into the optimised, constraint-compliant version of the Product Model.

Specific methodologies support the development of KBE applications, such as MOKA (Stokes, 2001), CommondKADS (Schreiber et al., 2000) and KNOMAD (Curran et al., 2010). It has been shown that there is still not full agreement in adopting a unique methodology, with some KBE applications being developed by not even following a specific one (La Rocca, 2012). As far as knowledge collection is concerned, a widely-used approach is to use MOKA's "ICARE" Forms: tables for collecting and storing standard knowledge (also called "Knowledge Units") under the five fundamental forms of "Illustrations" (past experiences), "Constraints", "Activities", "Rules" and "Entities" (physical object, their functions, or specific behaviours of those object).

In façades, KBE is not a common practice. Research efforts have focussed in rule-checking and quantity estimation through BIM models (Aram et al., 2014; Voss and Overend, 2012) and the creation of a Product Model for generation of shop drawings (Karhu, 1997). In the non-academic sector, some specific façade systems suppliers and sub-contractors have developed in-house digital tools that manipulate 3D models and include basic rules for guiding the design intent (Fuchs et al., 2015; Zahner, 2016).

3 METHODOLOGY

In this study, the present Knowledge-Based Engineering application was developed by following an iterative process. The knowledge, once captured, was increasingly structured, from natural language to more formal representations which, in turn, were enriched with new knowledge. The following methodology, which is based on previous methods such as MOKA and KNOMAD, was also developed for its simplicity and immediateness in informing domain experts in the construction sector about the knowledge-collection process and its potential benefits. This methodology should therefore be regarded as an effort to streamline the knowledge collection process and its formalisation, as well as the creation of KBE applications. The methodology is structured in the following parts:

1. The knowledge is retrieved through semi-structured interviews and informal meetings with knowledge experts. A document-based research can support this step, which by nature should integrate different sources and disciplines. Understanding the impact of the availability of knowledge versus its impact on the company is a fundamental step on which to focus the KBE development (Milton, 2007): the most prominent issues for the company should therefore become the main goal on which the knowledge collection stage should focus.
2. The captured knowledge is structured and stored into an online Knowledge Base (KB). MOKA "ICARE" forms (Stokes, 2001), standard tables representing concepts within the domain of discourse, can be used to support this stage. Hyperlinks, that connect the above-mentioned concepts, acquire a meaning thus creating a "Semantic Web", or ontology of interrelated concepts. The Knowledge Base therefore constitutes a useful resource alone, since it can be browsed by domain experts interested in understanding how their expertise lies within the Product Model. Maintenance programs can be implemented to keep the KB updated and accessible. New forms of data visualisation can be used to support and simplify the representation of this networks of concepts as this becomes complex, such as the JavaScript library D3.js (Bostock et al., 2011).
3. The outline of the Product Model is drawn by formal graphical languages such as Unified Modelling Language (OMG, 2016). UML can be used as an intermediate language to link the above knowledge collection and representation steps to the actual KBE tool implementation. Depending on the level of detail, UML can represent the Product Model's architecture (empty "class" boxes) for the management division of the company, or be more complete and used as a base for the final development of the application (so-called "forward engineering" approach).
4. The KBE application is developed and hard-coded, based on the above UML diagram. The chosen platform depends on the end-use the KBE application. Traditional KBE languages such as GDL

and AML or software platforms such as Catia KnowledgeWare can be used. Modern programming languages can also be used to build custom libraries to be plugged into existing software. Programming approaches that favour code reusability and extension, such as "spaghetti code", help maintain the application updated for knowledge change.

4 KBE APPLIED TO PRECAST, SINGLE-LEAF NON-LOADBEARING CONCRETE PANELS

4.1 Case study: precast single-leaf concrete panels produced in the Explore Industrial Park, Steetley, UK

4.1.1 Design

Precast single-leaf concrete panels, like any façade element, function as a barrier and filter between the internal and external environments in buildings. They must provide sufficient structural resistance and stiffness against self-weight and external actions such as wind, fire and other variable actions. Other required performances are thermal, luminous and acoustic comfort, air and water tightness, limited interstitial and surface condensation risk and, lastly, reduced energy losses through the building fabric.

The typical build-up of such panels consists of layers of different materials (Figure 1 - left). The external layer functions as a weathering protection and for aesthetics purposes. The structural layer, made from precast reinforced concrete, provides structural resistance and stiffness. Pre-formed insulation boards, with associated vapour barrier to avoid inner condensation, provide the required levels of thermal insulation. The thickness and physical characteristics of the above-mentioned layers vary on a project-by-project basis, given the unique combination of design conditions. The inner layer of the panels is usually completed on-site, with a stud frame supporting a double plasterboard giving a smooth inner finish.

Single-leaf panels can be either "loadbearing" or "non-loadbearing", whether the structural layer of the panel is or is not designed for bearing loads from other building elements. In case of non-loadbearing panels, the structural design is decoupled from the rest of the structure (but not vice versa), thus allowing local design models to be used.

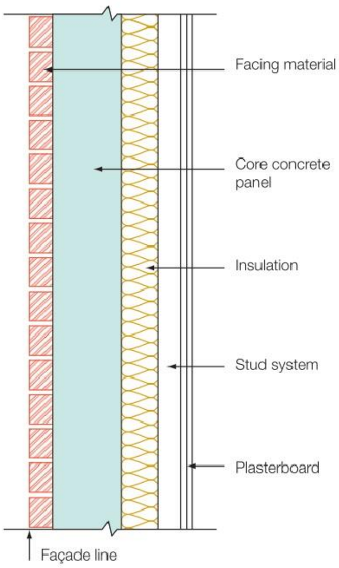

Figure 1. Vertical section of a precast single-skin concrete panel (left) and the "Bespoke Carousel" production line for concrete façade panels at the Laing O'Rourke's Explore Industrial Park (EIP), Steetley, UK (right).

Given their nature of prefabricated elements, single-leaf non-loadbearing panels require structural connections with the primary structure, which are usually realised through steel beams or plates. The structural design of those connections depends on the geometry and the relative position of the primary structure: as opposed to what happens in the above-mentioned concrete layer, the design of these elements is not decoupled from the primary structure. In particular, the position of the panel's bottom/top joints with respect to the structural slab and the insulation thickness determine the structural eccentricities that drive the design of the connection. Non-structural joints, such as sealants, mastics and fire-stops control the fluxes of air, water, noise and fire-driven heat through the remaining interfaces.

4.1.2 Manufacture

The panels under analysis are produced in the Explore Industrial Park, Steetley (UK), the precast concrete manufacturing facility owned by Laing O'Rourke. The factory presents three production lines, with increasing levels of bespokedness of the product, respectively: the High Speed Carousel (HSC), the Bespoke Carousel (BSC) and a traditional static area (Obinger et al., 2010). Single-leaf panels are produced in the BSC line, a semi-automated carousel (Figure 1 - right) where steel pallets holding the façade panels to be manufactured are transported through different stations. In the stations various activities, such as mould set-up, steel reinforcement and fittings assembly, and concrete pouring are performed. Stations have also limits in terms of geometry and weight of the panel; the use of standard elements from the supply chain, such as insulation, concrete and connection also drives the easiness, and therefore the cost, of manufacturing a specific solution. Logistical aspects, such as minimum / maximum dimensions and weights for transportation, must also be considered. An economic and feasible design of such panels should therefore be aware of these limitations, thus shifting the design activity towards a Design for Manufacturing and Assembly approach.

4.2 Results

4.2.1 Knowledge base and the Product Model's architecture (steps 1, 2 and 3)

The iterations of steps 1, 2 and 3 of the methodology (see Section 3) produce a Knowledge Base (KB) that stores design and manufacturing knowledge about the above-mentioned precast panels. The KB is stored in a website with private access. A main page lists all Knowledge Units (KU), which are stored into individual MOKA "ICARE" Forms. KUs contain information and knowledge about the Product Model such as the description of its physical components ("Entity-Structure" knowledge unit types) and their part-whole relationships. Figure 2 shows an interactive graphical representation of the generated taxonomy through a force-directed layout developed via the D3.js JavaScript library (Bostock et al., 2011).

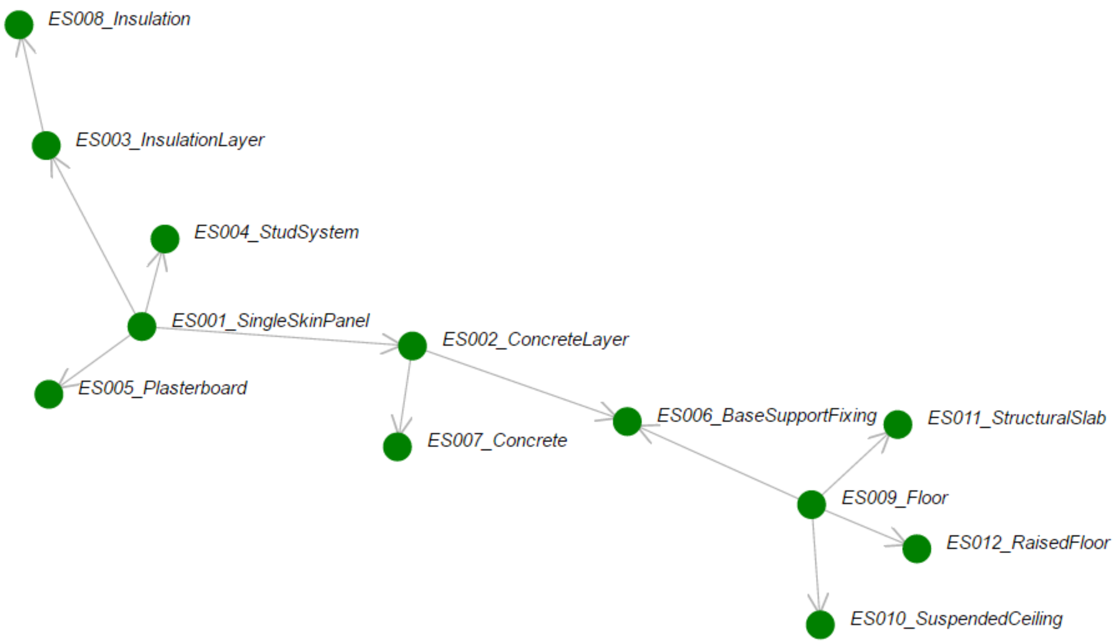

Figure 2. Online force-directed layout of the panel's taxonomy.

The Product Model also includes engineering rules and constraints associated to the design and manufacturing of the panels. New Knowledge Unit types such as "Constraints", "Rules" and "Entity-

Functions" are therefore introduced. The type of interrelationship between all KUs now depends on the two types of Knowledge Units which are connected. As an example, there are two links between an "Entity-Structure" and a "Constraint": the former KU is connected to the latter through a "has constraint" link. The inverse link, named "is applied to", is also present.

A Design Structure Matrix (Lindemann et al., 2009) was also used to represent the full network of KU and their relations (Figure 3). Rows and columns represent all Knowledge Units that describe the Product Model under investigation. The cells present different colours depending on the type of link. The cell in the i^{th} row and j^{th} column will be coloured if two identical KUs are connected. Conversely, the cell will be dark grey if two different KUs are linked. The diagonal shows a darker colour if the i^{th} Knowledge Unit is linked to more than one KU. Note that this matrix includes the same information about the taxonomy as the force-directed layout (green cells) in Figure 2 and extends it with more KUs (non-green cells).

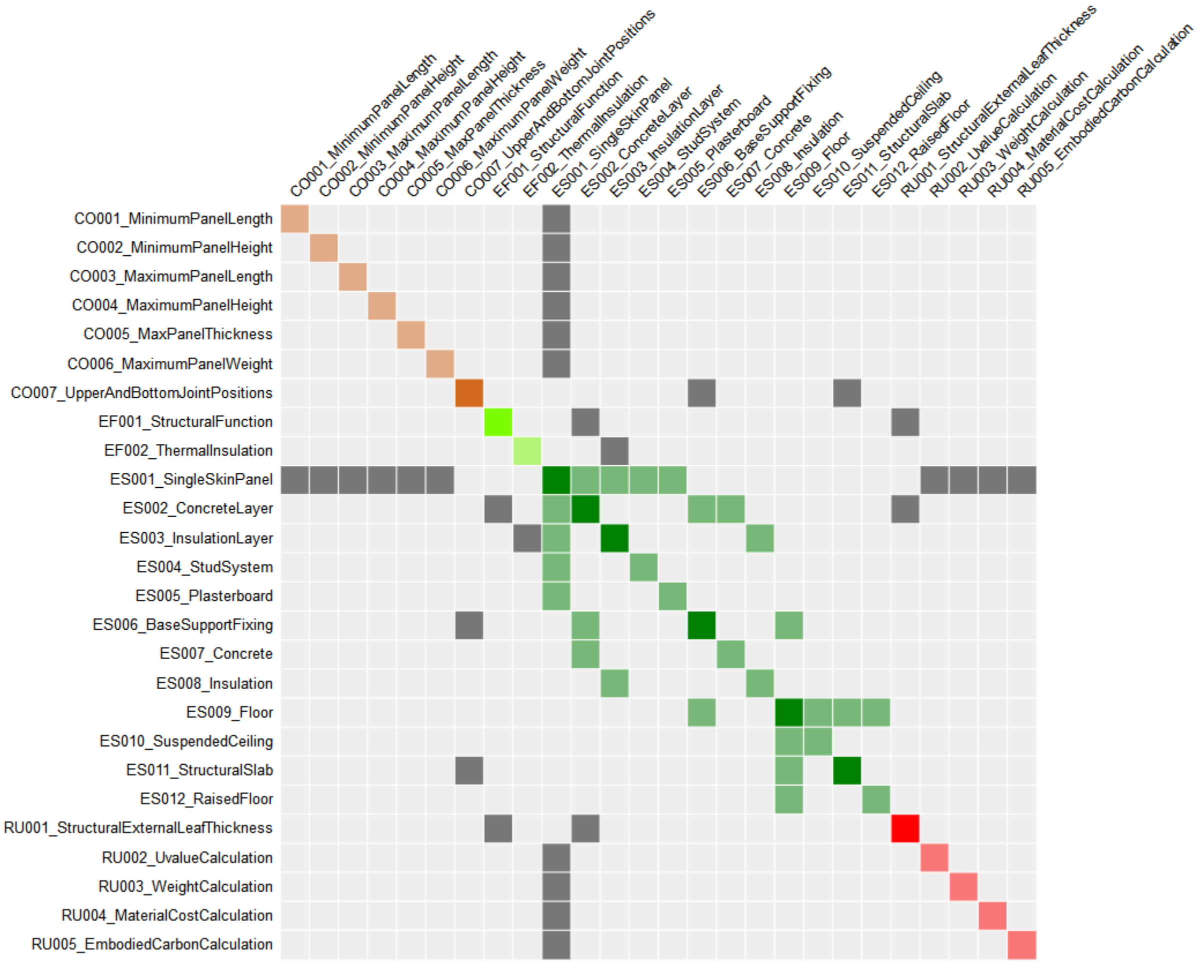

Figure 3. Online Design Structure Matrix showing the ontological view of the Product Model.

Finally, the above-generated ontology is represented in Unified Modelling Language. UML follows an object-oriented approach, with classes representing abstractions of a physical entities. Figure 4 shows a simplified version of the diagram, in which the "ComplianceChecker" class retrieves the user input, and validate them against the constraints in the "ConstraintDatabase" class and defines an output which is compliant to the above-created Knowledge Base.

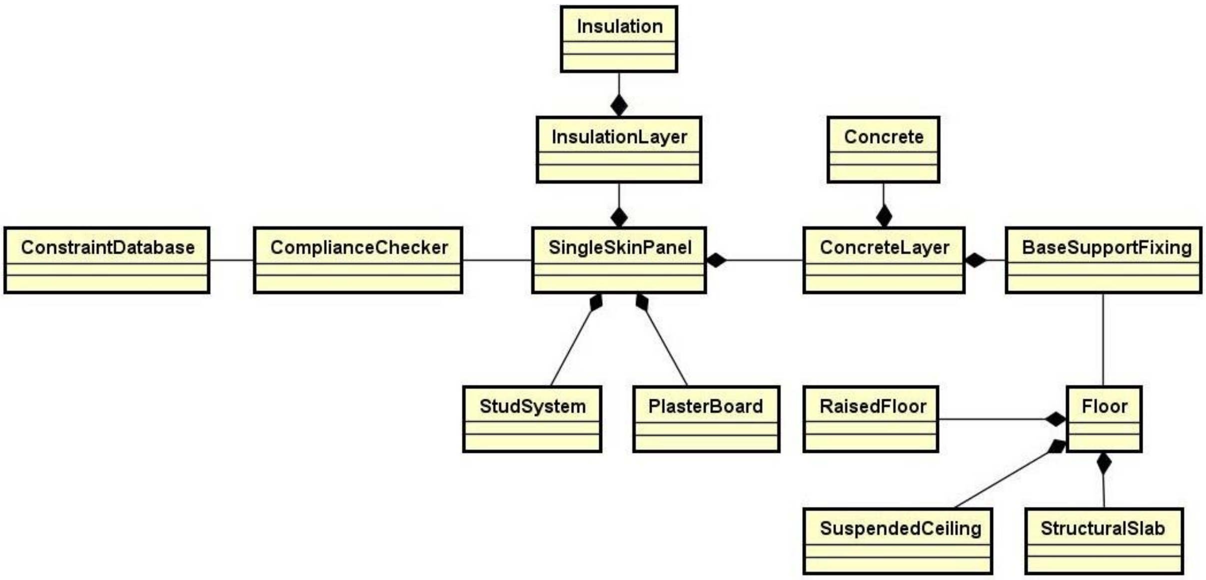

Figure 4. Simplified UML diagram of the Product Model

4.2.2 The KBE application (step 4)

The KBE application was developed by creating a C# library in Microsoft Visual Studio. Rhinoceros version 5 (Robert McNeel & Associates, 2016) and the Grasshopper plugin were used as a platform for the graphical visualisation of the Product Model (Figure 5). The use of the native .NET Framework language C#, with built-in functionalities for developing Windows applications, has permitted the creation of a Graphical User Interface that shows the predicted performances of the panel. The GUI can be accessed by double-clicking on the Grasshopper component ("Panel configuration options" window in Figure 5). The component takes some input directly from the Grasshopper environment (upper left window in Figure 5) so that can be plugged into existing native GH components.

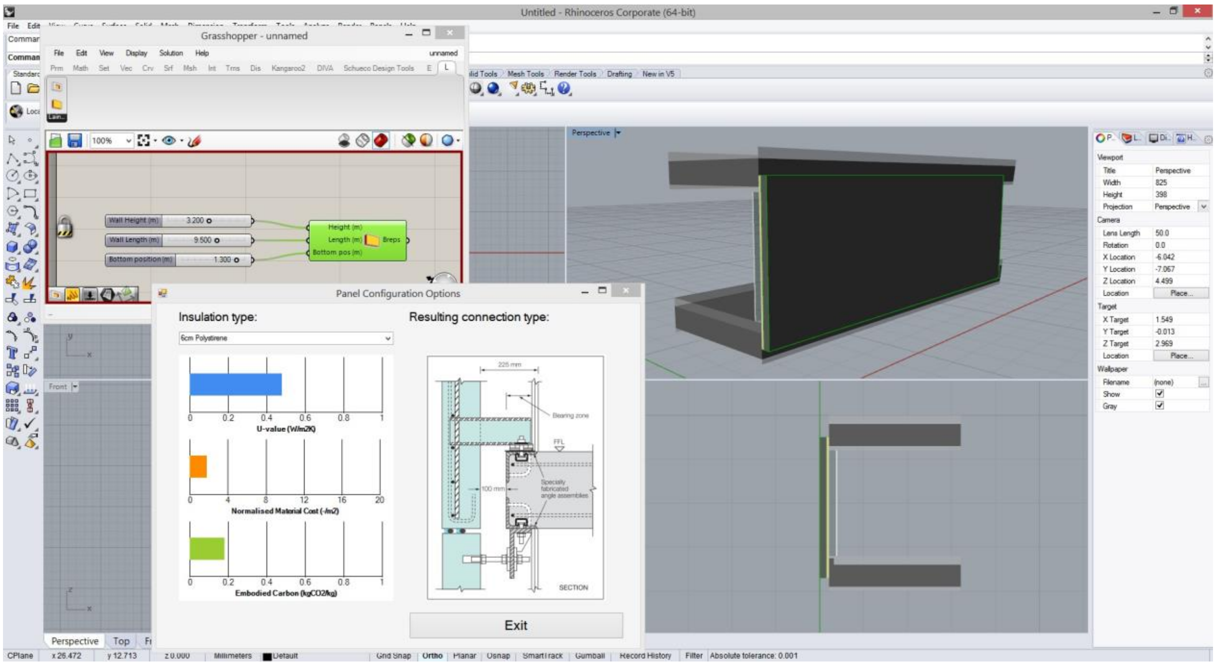

Figure 5. The KBE application

The design intent is therefore met while applying corrections based on the actual manufacturability of the panel. Performance indicators are displayed in real-time in the GUI. The list of rules, constraints and performance indicators can be found in Table 1. Some of the rules can be quite specific (such as the position of the panel with respect to the primary structure) and are not normally considered into the design of precast concrete panels.

Table 1. Implemented rules, constraints and performance indicators of the KBE application

Rules	U-value calculation Material Cost calculation Embodied Energy calculation Thickness of the structural layer calculation Type of bottom connection
Constraints	Min / Max panel height Min / Max panel width Maximum weight for lifting operations Position of the panel with respect to primary structure
Performance indicators ("Panel configuration options" window in Figure 5)	U-value Material Cost Embodied Energy

The KBE application automatically determines the main properties of the panel while applying constraints. The thickness of the reinforced concrete layer varies with the height of the panel, which in turn is limited by maximum manufacturing dimensions and weight. If the maximum weight is exceeded, e.g. by increasing the height of the panel, the application corrects the solution by reducing the length.
Geometrical features also influence the thermal performance indicator, the U-value, which is defined as:

$$U = \frac{\sum U_i A_i + \sum \Psi_i l_i + \chi_i}{\sum A_i} \quad (1)$$

Where U $\left(\frac{W}{m^2 K}\right)$ is the thermal transmittance of the panel, U_i is the thermal transmittance of 2D-elements, A_i is the frontal surface of 2D-elements, Ψ_i is the linear thermal transmittance of linear thermal bridges, L_i is the length of linear thermal bridges and χ_i is the point thermal transmittance of point thermal bridges. As the user select the appropriate geometry, the geometrical properties in Equation (1) are updated and shown in the GUI. As an example, a wide panel will increase thermal losses through the perimeter by increasing the l_i value. The type of insulation material can also be selected from the GUI, thus modifying the value of U_i. The insulation thickness determines a structural eccentricity, which in turn determines the type of base connection between panel and primary structure. Connections have standard χ_i value, initial cost and embodied carbon.

5 CONCLUSIONS

Façade design requires early integration of multiple design criteria, especially in terms of manufacturing aspects. Supporting the design process through automation of routine tasks and standard knowledge / information is therefore essential to increase productivity. This paper has shown how developing manufacturer-specific Knowledge-Based Engineering applications can be a possible approach. These applications can potentially reduce complexities and risks in the decision making process by tackling the above-mentioned issues.
A streamlined methodology for developing KBE applications has been presented in this paper, in which data visualisation techniques have been used to provide a more engaging graphical visualisation of the Product Model. Online force-directed layouts create a dynamic view of the Product Model's taxonomy, whereas online design structure matrices (DSM) help describe and infer about the ontological framework built around the Product Model. In this way, sector experts can interactively explore the knowledge embedded in the tool.
The increasing industrialisation process of precast concrete façades requires reduced risks and KBE applications can support designers in devising a correct design solution. The methodology used in this paper can be extended to new manufacturing technologies which are nowadays emerging in the construction sector. For example, large-scale 3D printing of buildings is introducing new design paradigms, in which designers cannot delay manufacturing checks until the end. Similarly, early involvement of suppliers and manufacturers is also forcing designers to work within the limits imposed a limited set of products and manufacturing capabilities / techniques. The ultimate goal is to achieve

complete understanding of trade-offs between the various stakeholders' needs, while controlling service life performance. KBE applications have the potential to satisfy this need.

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