Towards facades as Make-To-Order products – the role of Knowledge-Based-Engineering to support design

Jacopo Montali[1], Mauro Overend[1], P. Michael Pelken[2], Michele Sauchelli[2]

1   Glass and Facade Technology Research Group, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK, +44 7517 192 160, jm2026@cam.ac.uk.
2   Engineering Excellence Group, Laing O'Rourke Plc, Anchor Boulevard, Dartford DA2 6QH, UK

ABSTRACT

Building facades are Engineer-To-Order (ETO) products and, as such, they show unique features on a project-by-project basis. The partitioning of design tasks during the design and manufacturing process of these products, however, does not fully capture how specific design decisions influence other stakeholders' choices. This lack of design integration is most severe at early stages when a large proportion of initial costs, mostly driven by manufacturability aspects, is determined. This paper illustrates a methodology to build Knowledge-Based Engineering (KBE) applications to support early-stage design integration through the development of a facade Product Model for automatic rule checking and knowledge reuse. The main outcome is a preliminary framework for developing knowledge-based, digital tools to support and integrate facade design as well as different scenarios in which the tool can potentially be used, based on two types of procurement methods. A prototype of the tool is also shown here. The paper proposes a new paradigm where facade systems are considered to be more closely related to Make-To-Order types, rather than ETOs, in which the product is ready for fabrication and designers can rapidly explore the subcontractor's manufacturing capabilities and the implications of their design choices. Future work will include tool validation by applying the tool into a specific facade manufacturer's workflow.

1   INTRODUCTION

The unprecedented shift towards prefabrication and the increasing market competition in the AEC (Architecture, Engineering and Construction) sector require improved efficiency in the delivery of the final project, while concurrently controlling costs, risks and quality. Facades present several challenges for achieving these goals. Firstly, a degree of customisation always exists in facades; even a commercially-available system presents an almost infinite domain of possible solutions due to the number of infill products, end uses, climatic zones and orientations that make facades unique products, requiring new analyses each time the client requests it. For this reason, facade products are generally defined as Engineer-To-Order (Figure 1), since the client can influence the definition of the specification early on in the process prior to design stage. Secondly, the increasing number of requirements in facade design in recent years, from initial structural safety to a wider spectrum of criteria, has also made the design activity highly interdisciplinary and interdependent; a single optimal solution does not exist, but rather a set of acceptable solutions within the above-mentioned domain that meet different criteria, while respecting constraints, should be evaluated. Thirdly, prefabricated facades are highly modular systems, like many industrial products; the panelisation scheme identifies the fundamental unit of the product that will undergo serial production in the factory. This raises the issue of understanding manufacturing constraints, an aspect that, as shown by Voss & Overend (2012), is seen as the most influential aspect in driving costs in facades, especially during early stages of design.

Allowing variety while tackling both the interdependent nature and the view as industrial products of facades do, still presents a challenge. Collaborative approaches consisting of rapid meetings between specialists on specific design issues (e.g. concurrent engineering) are rarely, if at all, used in the fragmented AEC sector. A different approach is design automation through Knowledge-Based Engineering (KBE) applications, digital tools used for automation of design processes and reuse of standard knowledge. These applications have already been successfully used in other industries to reduce design time and errors, while optimising design. KBE applications have been mostly used for supporting the design of parts of so-called Make-To-Order products (MTO – Figure 1) such as the design of aircraft's wing ribs, cars' body-in-white and headlamps (Cooper, Fan, & Li, 2001). MTO products are normally associated with so-called 'Mass Customised' products, and the cost of developing a KBE application for MTO product types was made possible by the large number of units produced. KBE in facades should therefore focus on the reusable aspects of design by applying such tools

The aim of this paper is to introduce a methodology for developing KBE in facades, where the reusable part of manufacturing knowledge is embedded into KBE tools, thus relieving the design team from the burden of checking the manufacturability of the product while integrating multiple design criteria. The methodology is intended to provide a roadmap to facade designers and fabricators interested in digitising design criteria and knowledge. In this way, the facade product is seen as closer to a Make-To-Order type, where an existing package of knowledge is available and ready to be used, and the facade is designed for manufacture. The KBE tool therefore acts as an 'interim product configurator', where a non-fully defined design solution based on the configurator options is developed by the design team. The design solution is then detailed and completed by including the features that were missing from the KBE configurator, until the design is finalised.

Following a short background of KBE and its application in Section 2, the paper will cover the development methodology and possible use cases for facades in Section 3. Section 4 shows some initial results from the application of the proposed methodology. Discussion and proposals for future work are covered in Section 5 and 6, respectively. on multiple projects.
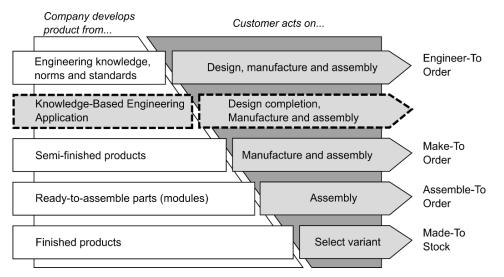
FIG. 1 Four product variant systems and the proposed approach. (Adapted from Hansen, 2003; and Rudberg & Wikner, 2004).

2 LITERATURE REVIEW AND RELATED WORK

Knowledge-Based Engineering (KBE) is an approach aimed at supporting design through the creation of specific tools that automate knowledge-intensive design processes from different and multidisciplinary sources. The main benefits are reduction in design times and errors, and design integration. KBE has been successfully applied in industries such as aerospace, automotive and shipbuilding. A general purpose tool for KBE development is called 'KBE system', whereas its actual implementation is called 'KBE application'. A complete review of KBE can be found in La Rocca, 2012.

The process of building a KBE application requires an integrated description of the fundamental concepts that govern the engineering problem or product and how they are interrelated. These include product parts and how they relate to the whole product; functional, physical and geometrical attributes; and associated constraints and rules. Different types of knowledge (e.g. tacit versus explicit) are integrated here. The resulting overall framework, called 'Product Model' (Stokes, 2001) or 'Ontology', is then implemented into the KBE application.

A KBE application works as a standard software application, where input data are retrieved from user interaction or databases, processed, and exported to specific, customised formats (Figure 2). The Product Model includes the product architecture and associated knowledge.

Methodologies have been developed to support the creation of a KBE application, such as MOKA (Stokes, 2001) and KNOMAD (Curran, Verhagen, & Van Tooren, 2010). To the authors' knowledge, these methodologies have never been applied in the facade sector, mostly due the lack of an economy of scale necessary to repay the development cost. It is therefore necessary to develop a methodology that allows rapid change and reuse of information and knowledge on several facade projects. Specific use cases can help identify the design step in which the tool is most effective.

In the facade sector, existing work in Knowledge-Based Engineering applied to facades is limited and lacks a common methodology. Karhu (1997) developed a Product Model of precast concrete facades based on a standard taxonomical structure of the facade panel that included the panel's main features such as standard panel-to-panel joint types. The focus here was on transferring information about the designed panels to other stakeholders. In more recent years, a digital KBE tool (Voss & Overend, 2012) was developed by Voss to evaluate the manufacturing limitations of the overall facade, such as a maximum cold-bending radius or overall manufacturing dimensions, by means of querying a Revit model. Aram et al. (Aram, Eastman, & Sacks, 2014) included knowledge about costs and quantity estimation to enrich the .IFC file exchange format for prefabricated concrete spandrels.

Very recently, some facade fabricators, such as Schueco and Zahner, have started to create product configurators that inform designers about the manufacturing capabilities of their systems and supply chain availability. Schueco's parametric tool (Fuchs, Peters, Hans, & Möhring, 2015) is a plugin for Grasshopper/Rhino, or for Revit, that automatically configures a highly customisable product that has been developed by Schueco. The plugin includes knowledge about the main manufacturing limits and preliminary structural design criteria. Zahner's CloudWall (Zahner, 2016) is an online platform for configuring bespoke facade patterns through freeform, vertical fins. The user manipulates a series of parameters that modify a 3D model of the facade, and receives a cost estimation for the configured product. These two examples therefore demonstrate a combined commercial need for selling highly bespoke products on the one hand, and digital tools supporting their design while controlling their manufacturing limitations on the other. This evidence is also supported by a survey undertaken by the Knowledge Transfer Network (2016); tools and technologies normally applied to mass customised products should be used for construction-related ETO products. Those tools should also integrate multiple design criteria and tackle the fragmentation of the construction market by looking at the facade product as a system, rather than the simple sum of its parts and functions.
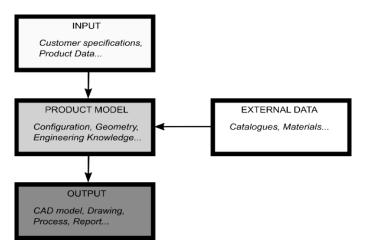
FIG. 2 High-level view of a Knowledge-Based Engineering System (Reddy, Sridhar, & Rangadu, 2015)

3 THE PROPOSED METHODOLOGY

3.1 THE BASIS OF THE METHODOLOGY

The proposed methodology for the development of KBE applications in facades is shown in Figure 3. It consists of four main steps that regularly increase the formality of the captured knowledge, from high to low level. The methodology presents the typical features of KBE methodologies, such as MOKA and KNOMAD, and includes the knowledge storage in standard forms ('ICARE' forms) and the use of UML modelling as an intermediate language. This methodology also presents some unique features that distinguish it from existing methodologies, such as its reduced level of complexity and steps to decrease the development time of KBE application, which is currently seen as one of the major limits. This methodology serves as a starting point for engineering and manufacturing companies that digitise standard knowledge and information for reuse and automation of design processes. It focuses particularly on facade systems and products that require the integration of multiple criteria, where the solution usually consists of a trade-off between those design criteria.
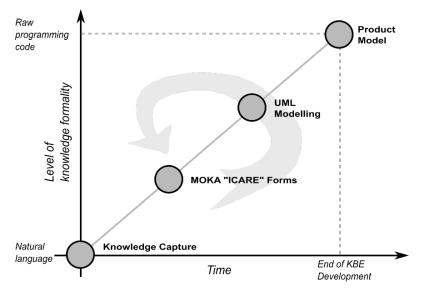

FIG. 3 Knowledge formalisation process, from natural language to raw programming code

3.1.1 Knowledge capture

The first goal of this step is to understand the type of knowledge that is available and its impact in terms of benefits for the company. If a specific design aspect is impossible to determine due to lack of analyses or experts, and, at the same time, is not relevant for the final delivery of the product, no implementation is needed. For those aspects that are not available but required, further studies might be needed.

Unstructured interviews with domain experts provide a sense of the major gaps in the design and manufacturing process and how to approach them. The interviewee must be aware of the future opportunities arising from the development of such applications in order to maximise his contribution. Semi-structured interviews can then be conducted to retrieve knowledge more systematically, once the problem has been set and the business case has been defined.

Document-based research is also useful in the retrieval of knowledge and information that would otherwise require excessive effort if people need to use it frequently (e.g. large PDF documents that contain guidelines and technical datasheets). Depending on the company, the availability of such documents varies. A standard methodology for capturing knowledge is illustrated by Milton (2007) and an example of aerospace application for Fibre Metal Laminate (FML) panels has been developed by Emberey & Milton (2007).

3.1.2   Structure knowledge through MOKA ICARE Forms

The next step structures knowledge by selectively sorting, storing and linking it into a Knowledge Base, a structured repository where knowledge information is easily accessible. The creation process of a Knowledge Base consists of the analysis and categorisation of all the concepts related to the design and manufacture of the product in question.

The process of creating the Knowledge Base requires the identification of the fundamental units representing knowledge. ICARE forms (Stokes, 2001) - standard tables representing a type of unit of knowledge - can be used for this purpose. Table 1 shows the type of knowledge these forms can represent.

FORM	REPRESENTED KNOWLEDGE
Illustration	Experience on past projects
Constraint	Physical / geometrical limits on product / processes
Activity	Single step in design and manufacturing activity
Rule	Design / manufacturing engineering rule
Entity	Physical entity, function or change in state of a product

TABLE 1   MOKA ICARE Forms

Knowledge is thus implemented on tables and stored into these standard forms, which are then cross-referenced (e.g. through hyperlinks, if forms are developed in HTML), resulting in a network of inter-linked concepts. An example is shown in Figure 4 where an 'Entity' form is referenced to a 'Rule' form. Graphical representations of the network help in the visualisation of the overall network and the correlation between different concepts. The Knowledge Base is then validated against the opinion of domain experts, which helps to correct or extend it.

FIG. 4 MOKA 'Entity' form representing the structural layer of a precast concrete single-skin panel, linking to a 'Rule' form containing a simplified engineering rule for dimensioning the concrete thickness

3.1.3 Development of the Product Model architecture via UML Modelling

Unified Modelling Language (UML, 2016) is used to define the basic structure of the Knowledge-Based tool, based on the Knowledge Base. The approach here is to model each knowledge unit through an object-oriented approach, where each physical object is represented by a class as characterised by the following features:

— Attributes: these represent all the geometrical and physical features of the physical components, i.e. the associated variables (e.g. height, width, thermal conductivity, cost per cubic metre).
— Behaviours: these represent the change of the state of the object belonging to the class. They are usually represented by functions, i.e. blocks of code that perform a specific task (e.g. change in insulation type depending on the presence of different fire requirements).

UML also represents the type of interrelationship between classes, such as inheritance, association, composition and aggregation. The taxonomy of the product under investigation (defined as the hierarchical classification of the sub-components) is therefore created; Figure 5 shows a typical 'composition' link between the product and its subcomponents, represented by a black diamond, describing the 'has-a' relationship between physical entities. Once the taxonomy has been defined, the design and manufacturing knowledge is incorporated into the taxonomy to form a lower-level ontological framework of the product.
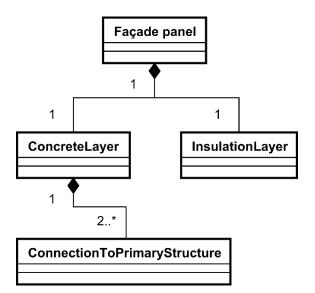
FIG. 5 Simplified UML diagram showing the taxonomy of a facade product. Each yellow box corresponds to an 'Entity' MOKA form.

3.1.4   Build the Product Model

The Product Model is then translated into a programming code, based on the software architecture defined by the UML diagram. The type of programming language can be either a specific KBE system, such as AML, ICAD or GDL, or a general-purpose programming language. A standalone software or a plugin can be chosen as platform.

The overall process (steps 1 to 4) is iterative and adopts an agile approach, in which new knowledge is included, or replaces outdated concepts. The development of a software architecture that allows quick extensions and modifications is therefore desirable. Object-orientation, in this sense, allows the creation of custom libraries of standard objects with associated knowledge that can be reused whenever a new KBE tool for a new product is created (e.g. the insulation material of a single-skin precast concrete panel is identical to that used for a loadbearing, precast concrete sandwich panel in terms of intrinsic properties such as thermal resistance and material cost).

3.2   USE-CASE SCENARIOS

The use of the Knowledge-Based tool is analysed here from the point of view of a facade manufacturer at design stages, in order to support design development. Consortia of companies could also be formed to cut development costs while integrating multiple manufacturing capabilities or product data in a single platform. Three possible use cases are shown, based on two different British procurement methods (RIBA, 2013) in which the manufacturer may or may not be appointed to develop the design from the early stages. Online process maps in a BPMN notation ('BPMN,' 2017) of the above use cases has been developed for clarity (author's webpage, 2016).

— Case 1: KBE tool available to download for design teams for use during early-design stages (e.g. RIBA 3) of a Design-Bid-Build (DBB) procurement method. In this case, a design team developing the design solution is using a manufacturer-specific KBE tool to evaluate the level of early 'tenderability' by that specific manufacturer, including preferred materials from the supply chain. Existing examples of KBE-like applications used in this sense are the Schueco Parametric System or Zahner's CloudWall. If the design solution does not comply with the configurator, then the design team should consider a bespoke solution.
— Case 2: KBE tool used by a facade manufacturer to inform and support a design team during early design stages (e.g. RIBA 3) in DBB. This case considers a situation where the knowledge of the facade manufacturer is protected by confidentiality. The manufacturer therefore provides a service to the design team by using the KBE tool internally for rapid and quick support activities.
— Case 3: KBE tool used by the project team across design stages in a Design-Build (DB) environment. In this case, the tool becomes central to the design team, whose activity is the development of solutions within the space defined by the tool. If the KBE developers form part of the design team, the possibility to tailor the tool on-the-go (e.g. including more consideration from the design perspective or increasing the level of details) through agile software development should be considered. Cases 1 and 2 require an a priori development of the tool, which is then issued and used. Case 3 instead requires ongoing development as the project progresses, based on a pre-constructed base (e.g. a .dll library).

4   PRELIMINARY RESULTS

The expected result from the present research is the development of a prototype KBE tool for a chosen facade type manufactured by a specific company, which will consider manufacturing limits, design constraints and performance indicators. The methodology described above has already been applied to a specific facade typology (Montali, Overend, Pelken, & Sauchelli, 2017). The example refers to a case study of a precast concrete unit comprising single skin panels manufactured in a specific facility, the Explore Industrial Park in Steetley, UK. Knowledge was collected by conducting interviews with experts and by collecting design guidelines. The generated Knowledge Base has been represented in a graphical form through a Design Structure Matrix (Lindemann, Maurer, & Braun, 2009) as shown in Figure 6. The matrix presents the ICARE forms in rows and columns; if the generic cell of the matrix is checked, then a semantic link exists between the two forms.
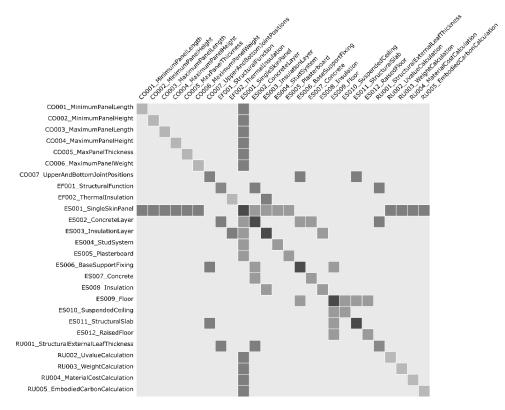
FIG. 6 Design Structure Matrix representing the knowledge associated to the design and manufacture of single skin precast concrete panels (Montali et al., 2017).

Figure 7 represents the generated knowledge based application, developed in Rhino / Grasshopper by creating a custom Grasshopper component in C#. The application requires geometrical (overall dimensions of the panel and position relative to the primary structure) and physical (insulation type) inputs, and returns a geometry that respects some pre-determined constraints, as well as some performance indicators such as U-value, material cost and embodied carbon.
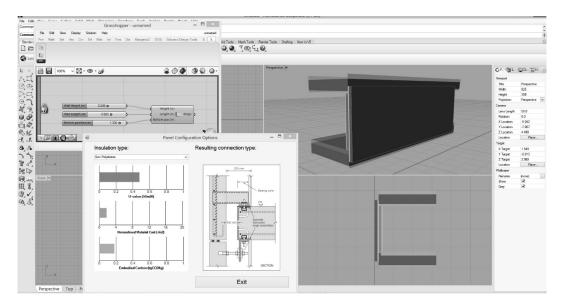

FIG. 7 Developed KBE application for the design of single skin precast concrete panels (Montali et al., 2017).

5 DISCUSSION

This paper has proposed a preliminary framework for developing digital Knowledge-Based Engineering (KBE), three use cases for two common British procurement methods. The framework can be adopted by companies to develop digital tools that inform design teams about their detailed manufacturing and supply chain capabilities. An example of application to a prefabricated, precast concrete panel has been shown to prove the concept. By using those tools, design teams can start to understand the limitations of designing a solution that will eventually be produced by a specific manufacturer, while expressing their design intent. As product development moves increasingly towards 'Mass Customisation', the use of KBE systems might appear to be counterintuitive, given the reduction in design freedom. However, the authors believe that facades should be considered as highly engineered products, the likes of which have not yet been manufactured, with some a priori design knowledge that takes into account some limitations, be they physical or performance-based. This is the onus for unleashing the 'Mass' part while not reducing the 'Customisation' aspect. The shift towards Make-To-Order types should be therefore regarded as asymptotic, since the design of MTO is completed before the client develops the specifications; the space of solutions is also more limited. Another fundamental aspect in achieving Mass Customisation that has not been considered in this paper is the role of an agile and broad supply chain.

6 FUTURE WORK

Future work will include the development of the KBE tool, its application on case studies, and subsequent validation through the creation of specific merit indices. Possibilities for multi-objective optimisation will also be explored.

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