

TOWARDS FACADES AS MAKE-TO-ORDER PRODUCTS: THE ROLE OF KNOWLEDGE-BASED ENGINEERING TO SUPPORT DESIGN



Jacopo MONTALI¹, Mauro OVEREND¹, P.Michael PELKEN², Michele SAUCHELLI²

¹ *Department of Engineering, University of Cambridge, Cambridge, UK*

² *Engineering Excellence Group, Laing O'Rourke Plc, Dartford, UK*



Abstract

Building façades 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 where a large ratio of initial costs, mostly driven by manufacturability aspects, is committed. This paper illustrates how Knowledge-Based Engineering can potentially support early-stage design integration through the development of a façade Product Model for automatic rule checking and knowledge reuse. The focus is on assessing the façade manufacturability of prefabricated products at early stages, with the subcontractor assisting the design team through a digital tool that includes the Product Model. A preliminary framework for the development of knowledge-based, digital tools to support and integrate façade design is presented. Different use-case scenarios are analysed, based on two types of procurement methods. The paper also proposes a new paradigm where façade systems are considered as closer to Make-To-Order types, rather than ETO, 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 prototyping and subsequent validation by applying the tool into a specific façade manufacturer's workflow.

Keywords

Façade design, Design automation, Product configuration, Knowledge-based Engineering, Manufacturability.

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. Façades present several challenges to achieving these goals. First, a degree of customization always exists in façades: even a commercially-available system in fact presents an almost infinite domain of possible solutions due to the number of infill products, end uses, climatic zones and orientations that makes facades unique products, requiring new analyses each time the client requests it. For this reason, façade products are generally defined as Engineer-To-Order (Figure 1), since the client can influence the definition of the specification upstream in the process until the design stage. Second, the increasing number of requirements in façade 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. Third, prefabricated façades are highly modular systems like many industrial products: the panelisation scheme identifies in fact the fundamental unit of 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 façades, especially during early stages of design.

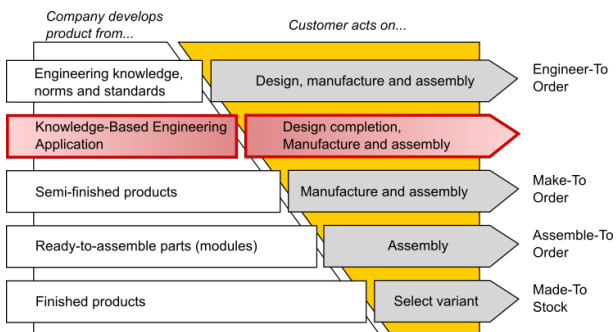


Figure 1: Four product variant systems (grey) and the proposed approach in red (adapted from Hansen, 2003 and Rudberg & Wikner, 2004)

A possible approach to allow variety while tackling both the interdependent nature and the view as industrial products of façades is design automation through Knowledge-Based Engineering (KBE)

applications: digital tools used for automation of design processes and reuse of standard knowledge. These applications are already used successfully in other industries to reduce design time and errors, while optimising design.

The aim of this paper is to introduce a methodology for applying KBE to façades 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 façade designers and fabricators interested in digitalising design criteria and knowledge. In this way, the façade product is seen as closer to a Make-To-Order type (Figure 1), where an existing package of knowledge is available and ready to be used, and the façade is designed for manufacture. The KBE tool acts therefore as an "interim product configurator", where the final design solution is developed by the design team, based on the configurator options.

The paper, after providing a short background of KBE and its application in Section 2, will cover the development methodology and possible use cases for façades in Section 3. Section 4 will conclude with discussion and future work.

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 / product and how they are interrelated, such as product parts, how they relate to the whole product and their function, physical and geometrical attributes, 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.

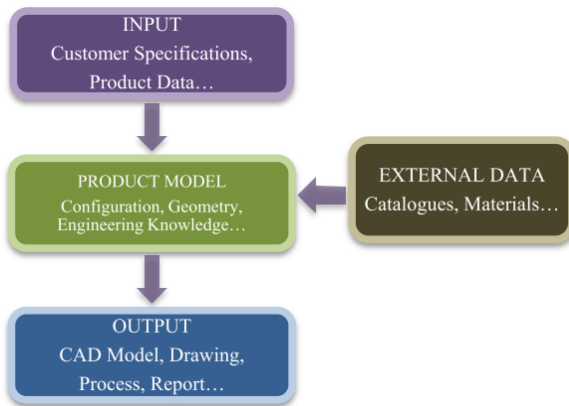


Figure 2: High-level view of a Knowledge-Based Engineering System

Methodologies have been developed to support the creation of 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 façade sector, mostly due the lack of an "Economy of Scale" to repay the development cost. It is therefore necessary to develop a methodology that allows rapid change and reuse of information on several façade projects. Specific use-cases can help identify the design step in which the tool is most effective.

In the façade sector, existing work in Knowledge-Based Engineering applied to façades is limited and lacks a common methodology. Karhu (1997) developed a Product Model of precast concrete façades. In more recent years, a digital tool was developed to evaluate the manufacturing limitations of the overall façade (Voss & Overend, 2012) or to include knowledge about costs and quantity estimation in the .IFC file exchange format for prefabricated concrete spandrels (Aram, Eastman, & Sacks, 2014). Very recently, some façade 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.

3. The proposed methodology

3.1 The basis of the methodology

The proposed methodology for the development of KBE applications in façades is shown in Figure 3. It consists of four main steps that regularly increase the formality of the captured knowledge, from high level to low level. The methodology presents the typical features of KBE methodologies such as MOKA and KNOMAD, such as the knowledge storage in standard forms ("ICARE" Forms) and the use of UML modelling as an intermediate language. This methodology serves

as a starting point for engineering and manufacturing companies that digitalise standard knowledge / information for reuse and automation of design processes. It is particularly addressed to façade systems and products in general that require an integration of multiple criteria and where the solution usually consists of a tradeoff between those design criteria. It should also be regarded as a preliminary framework, with each step to be developed further.

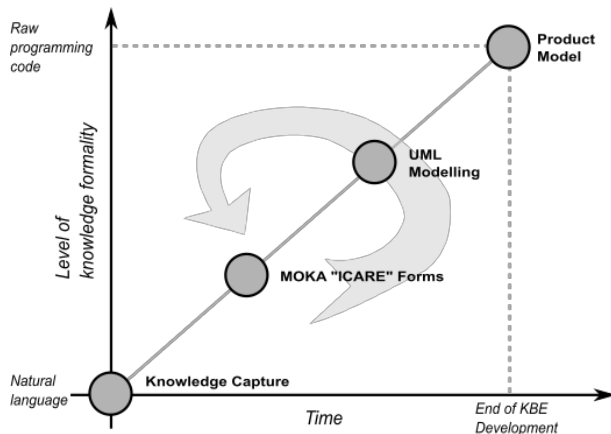


Figure 3: Knowledge formalisation process, from natural language to raw programming code

3.1.1 Knowledge capture

The first goal of this step is to understand which type of knowledge is available and its impact in terms of benefits for the company. Unstructured interviews with domain experts provide a sense of the major gaps in the design and manufacturing process and how to approach them. Semi-structured interviews are then conducted to retrieve knowledge more systematically. Document-based research is also useful to retrieve knowledge and information that would otherwise require excessive effort to be used repetitively by humans (e.g.: large PDF documents that contain guidelines and technical datasheets). 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. The Knowledge Base consists of a structured repository where knowledge is easily accessible. ICARE forms (Stokes, 2001), standard tables representing a type of unit of

knowledge, are used for this purpose. Table 1 shows the type of knowledge these forms can represent.

Table 1. MOKA ICARE Forms

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

ICARE forms are then cross-referenced (e.g.: through hyperlinks, if forms are developed in HTML), thus 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 visualize the overall network and the correlation between different concepts. The Knowledge Base is then validated against the opinion of domain experts that help correct or extend it.

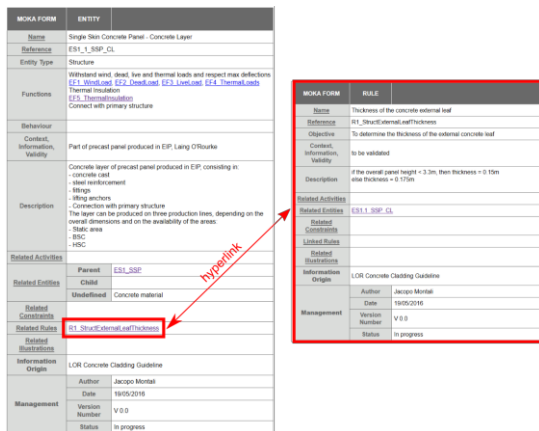


Figure 4: MOKA “Entity” form representing the structural layer of a precast concrete single-skin panel, linking to a “Rule” form containing a simplified engineering rule for dimensioning the concrete thickness

3.1.3 Develop 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 above-created 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. Attributes (e.g.: geometrical / physical features) and behavior (e.g.: weight calculation) are associated to each class. The type of interrelationship between classes, such as inheritance, association, composition and aggregation are also represented. The taxonomy of the product under investigation (defined as the hierarchical classification of the sub-components) is therefore created (Figure 5). The addition of the associated design and manufacturing knowledge to the taxonomy forms the ontological framework of the product.

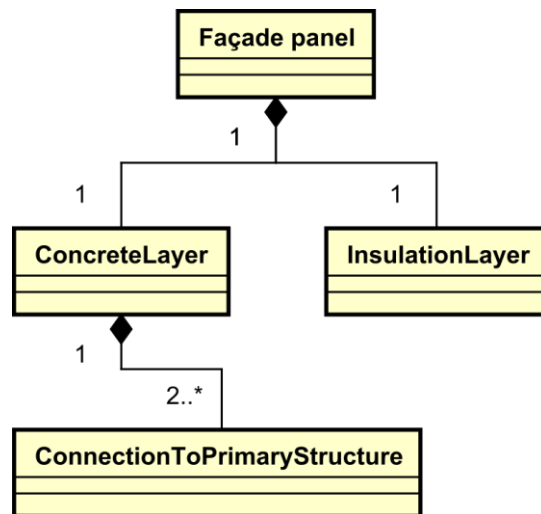


Figure 5: Simplified UML diagram showing the taxonomy of a facade product. Each yellow box corresponds to an “Entity” MOKA form.

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 plug-in 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 here analysed from the point of view of a façade manufacturer during design stages to support design development. 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 for developing the design since early stages. A graphical view in BPMN notation (BPMN, 2016) of the above use-cases can be viewed at the following [link](#) (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 façade manufacturer to inform / support a design team during early-design stages (e.g.: RIBA 3) in DBB. This case considers a situation where the knowledge of the façade 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 to develop solutions within the space that 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.: by including more design consideration from the design side or increasing the level of details) through an agile software development should be considered.

Case 1 and 2 require an “a priori” development of the tool, which is then issued and used. Case 3, instead, requires an ongoing development as the project progresses, based on a pre-constructed base (e.g.: a .dll library).

4. Discussion, expected results and future work

This paper has proposed a preliminary framework for developing digital Knowledge-Based Engineering (KBE), as well as 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. 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, not manufactured yet, with some a priori design knowledge that takes into account of some limitations, be they physical or performance-based. This is the onus for unleashing the “Mass” part while not sensibly reducing the “Customisation” aspect. The shift towards Make-To-Order types should be therefore regarded as asymptotic, since MTO have their design completed before the client develops the specifications: the space of solutions is also more limited. Another fundamental aspect to achieve Mass Customisation and that it has not been considered in this paper is the role of an agile and broad supply chain.

The expected result from the present research is the development of a prototype KBE tool for a chosen façade type manufactured by a specific company, which will take into account manufacturing limits, design constraints and performance indicators.

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

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References

- Aram, S., Eastman, C., & Sacks, R. (2014). A Knowledge-Based Framework for Quantity Takeoff and Cost Estimation in the AEC Industry Using BIM. In *The 31st International Symposium on Automation and Robotics in Construction and Mining*.
- Author’s webpage. (2016). Retrieved from http://www2.eng.cam.ac.uk/~jm2026/jm_web/ResearchWork/kbe-tool-use-cases/index.html

- BPMN. (2016). Retrieved from <http://www.bpmn.org/>
- Curran, R., Verhagen, W. J. C., & Van Tooren, M. J. L. (2010). The KNOMAD methodology for integration of multi-disciplinary engineering knowledge within aerospace production. *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, (January), 1–16.
- Emberey, C. L., & Milton, N. R. (2007). Application of Knowledge Engineering Methodologies to Support Engineering Design Application Development in Aerospace. *7th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, (September), 18–20.
- Hansen, B. L. (2003). *Development of Industrial Variant Specification Systems*. B.L. Hansen, Development of industrial variant specification systems, Ph.D. Thesis. Technical University of Denmark, Lyngby, 2003.
- Karhu, V. (1997). Product Model Based Design of Precast Facades. *ITcon Journal*, 2(November 1996).
- La Rocca, G. (2012). Knowledge Based Engineering: Between AI and CAD. Review of a Language Based Technology to Support Engineering Design. *Advanced Engineering Informatics*, 26(2), 159–179. <http://doi.org/10.1016/j.aei.2012.02.002>
- Milton, N. R. (2007). *Knowledge Acquisition in Practice: A Step-by-step Guide* (1st ed.). book, Springer-Verlag London.
- RIBA. (2013). RIBA Plan of Work 2013 Overview.
- Rudberg, M., & Wikner, J. (2004). Mass customization in terms of the customer order decoupling point. *Production Planning & Control*, 15(4), 445–458. <http://doi.org/10.1080/0953728042000238764>
- Stokes, M. (2001). *Managing Engineering Knowledge – MOKA: Methodology for Knowledge Based Engineering Applications*. In *Professional Engineering Publishing Limited*. ASME Press.
- UML. (2016). Retrieved from <http://www.uml.org/>
- Voss, E., & Overend, M. (2012). A Tool that Combines Building Information Modeling and Knowledge Based Engineering to Assess Façade Manufacturability. *Abs 2012*.