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# Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends

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## ABSTRACT

The use of prefabricated façades provides a timely means to increase efficiency in the delivery of buildings, while maximising the expected environmental service performance. In order to achieve high performance and low cost, these products require manufacturability and supply chain knowledge to be integrated earlier than usual in the design process. Knowledge-Based Engineering (KBE) applications can potentially fulfil this need by providing a digital Product Model that informs designers about manufacturability aspects and expected performance. This paper explores the currently available digital tools, as well as KBE and its applicability in façade design. It is first demonstrated that there is a fundamental gap in state-of-the-art digital tools: rather than integrating design principles and manufacturing constraints, existing and emerging tools continue to focus on single disciplines with no consideration for the actual manufacturing stage. The applicability of KBE is then evaluated by reviewing the current use of this approach in the building and other industries, namely, aerospace and shipbuilding. It is found that, although KBE is rarely used in façade design, there are significant opportunities for it to be applied in this sector, due to the similarity in terms of design tasks and priorities with the two other industries reviewed in this paper.

## Introduction

### Background

The AEC (Architecture, Engineering and Construction) sector is experiencing an unprecedented increase in complexity motivated by continuously evolving construction standards, ambitious architectural aspirations and international competition requiring a reduction in delivery times. In this sense, the façade plays a key role as it has a significant impact on the functional, economic and aesthetic aspects of the overall building.

The AEC sector is undergoing an increasing shift towards prefabrication to achieve higher environmental and quality standards, and to increase the productivity of the sector (Construction Industry Council, 2013). Prefabrication could provide a solution to the stagnant productivity levels of the AEC sector in the last 20 years, a trend which contrasts with the significant productivity improvements achieved by the manufacturing sector during the same time span (McKinsey & Company, 2015). As the level of involvement of the customer increases, prefabrication technology shifts to

the so-called 'flexible industrial prefabrication' (Eekhout, 2009), in which façades therefore become highly customised industrial product.

Industrial products can be classified depending on the level of client involvement in the design, manufacture and assembly process (Figure 1), ranging from merely choosing between the alternative final products available (Made-To-Stock), to the increasing degrees of customisation (Assemble-To-Order (ATO) / Modify-To-Order / Engineer-To-Order (ETO)). Façades are ETO products, since each time a product is requested by the client, the delivery process starts from the design stage. This approach, despite yielding bespoke products, adds time and risk to the overall delivery time of the façade. Bespokedness in façades greatly varies from a one-off, traditionally crafted product, to customised solutions within a set of pre-determined systems (e.g. prefabricated concrete panels), to the selection of standard systems (e.g. off-the-shelf curtain wall systems). A reduced level of bespokedness, for example, through the definition of standard system types, may decrease the design effort and result in a quicker delivery process, but this must be balanced with the broad domain of possibilities that is required to fulfil architectural freedom.

The higher risk associated with ETO product delivery may lead to higher initial costs and lower environmental performances, the latter being the 'sword of Damocles' of the built environment, given the high impact of this sector on the overall carbon emissions (Eurostat, 2016). Product design is nowadays becoming increasingly aware that decisions made early in the design process significantly affect cost and environmental impact: for this reason, there is a growing tendency to bring knowledge, which is normally used in later stages, upstream into the design stage (Chandrase-garan et al., 2013). The need for more control of design knowledge is more evident when new manufacturing technologies are adopted: Labonnote, Rønnquist, Manum, and Rüther (2016), in reviewing the potential of additive manufacturing in construction, stress the importance of new design paradigms supported by parametric tools. The tools will capture manufacturing limitations and expected performance to determine the best trade-offs between the governing design parameters, thereby creating more awareness in the decision-making process. The need to adapt design to novel tools/techniques is named by Bock (2015) as Robot-oriented design (ROD).

The aerospace, automotive and shipbuilding industries have developed digital tools that support design through automation of reusable knowledge, called Knowledge-Based Engineering (KBE) systems. Design tools normally require the users to input their own knowledge; conversely, tools
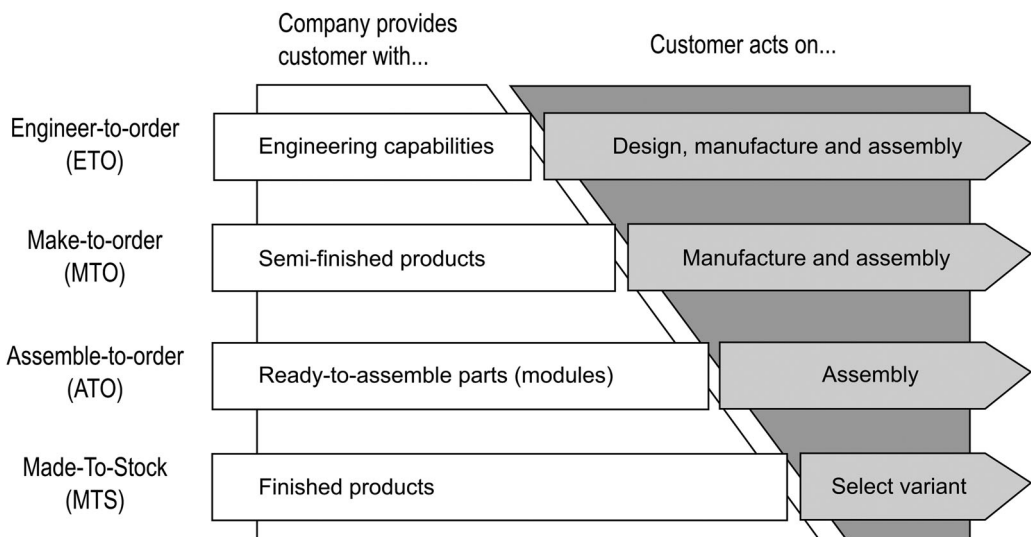


**Figure 1.** Types of product variant specification, adapted from Hansen (2003) and Rudberg and Wikner (2004): building façades are classified as 'Engineer-To-Order'.

following a 'Knowledge-Based' approach place the emphasis on knowledge digitalisation into the software application itself, thus resulting in an automatic and improved design support. KBE systems are represented by a Product Model (Stokes, 2001) that includes various forms of knowledge from different engineering disciplines and combines them into a tool which captures their inter-relationships. KBE is also seen as a potential solution to automatically support ETO product development (Willner, Gosling, & Schönsleben, 2016). The application of KBE to building façades would thus embed knowledge about how the façade product is designed, manufactured and assembled through the Product Model.

This paper aims to explore new opportunities to use KBE systems as digital tools for supporting the design of building façades, by reviewing existing state-of-the-art tools for façade design and KBE systems in the façade sector and in other industries. To this end, the paper firstly identifies the current major challenges affecting façade design. This is followed by a review and classification of currently available façade design tools and how KBE systems are currently used in other industries and in the façade sector. The paper ends with overarching conclusions and future work.

## Façade design process and related challenges

### Façade design process

Façade design is a highly interdisciplinary and interdependent design activity wherein the façade consultant mediates the design solution between subcontractors, the other members of the engineering design team, the architect, the cost consultant and the client. The process follows the typical conceptual/developed/detailed workflow. The levels of complexity increase as the design process progresses from the early-stage definition of basic geometrical features and broad performance criteria to the detailed information for production and installation. The focus therefore moves from the whole-building, in which the generic features are defined (e.g. window-to-wall ratio), to more specific analyses for assessing the performance on a detailed level (e.g. 2D/3D finite element analyses of heat conduction at interfaces between different façade elements). Iterative checks are conducted at each stage to ensure that design requirements are met as the design progresses (Figure 2). These include: manufacturability, cost, expected performances and the architect's design intent are evaluated. The process does not normally back cycle except for unforeseen design errors or manufacturing
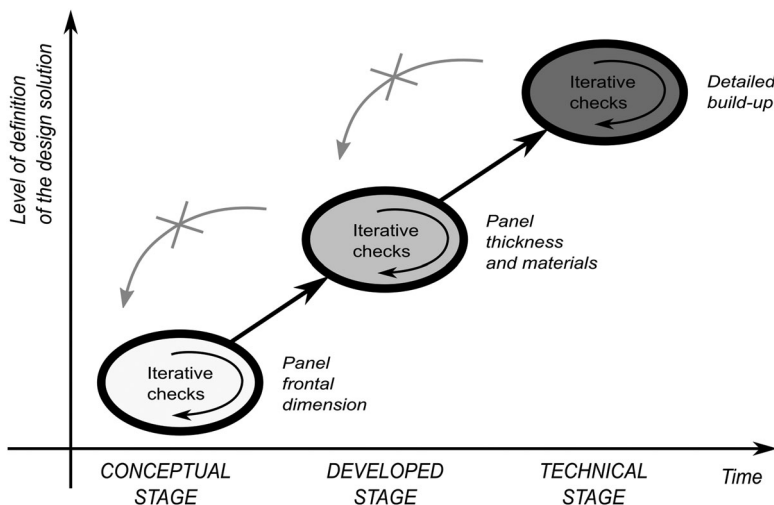


**Figure 2.** Schematic representation of the façade design process.

constraints (Kassem & Mitchell, 2015). A detailed, BPMN-based process map of a façade design process for a traditional procurement route has been developed by Voss, Jin, and Overend (2013).

The contractual arrangement between stakeholders affects the ease in delivering the façade product. Traditional forms include a design team appointed for developing a design solution that subsequently forms part of the tender documentation, over which potential façade subcontractors bid. There is also a growing trend to use procurement routes that engage a general contractor earlier in the process (e.g. Design – Build, Integrated Project Delivery), thus leading to integrated teams that merge knowledge from both design and construction; the risk of incurring design errors is therefore limited. Methods that integrate the manufacturing, installation and procurement stages in the design process of the building, including façades, and that pursue a Design for Manufacture and Assembly approach, have been shown by the Royal Institute of British Architects (RIBA, 2013a).

## Current challenges

Façade design presents the following challenges:

- **Intrinsic interdependencies of the design process**. The design process requires an understanding of how initial choices influence later stages and, conversely, how later stages should drive initial design steps, such as the circular interrelation between panelization scheme (frontal dimensions), thickness and detailing of the internal build-up, while meeting production-related constraints (Henriksen, Lo, & Knaack, 2016 – Figure 2).
- **Manufacturability information challenges**. Different authors have shown that one of the major challenges encountered by façade consultants is to meet the design intent of the architect while respecting a series of constraints (Karsai, 1997; Voss & Overend, 2012) coming from manufacturers (Vaz, Al Bizri, & Gray, 2008). In a traditional delivery method, such as Design-Bid-Build (RIBA, 2013b), different subcontractors informally support the design team before the tender stage (Eastman, Sacks, Panushev, Aram, & Yagmur, 2009; Voss & Overend, 2012). Integrating various types of knowledge from different sources into design choices still represents a challenge. In more integrated processes such as Design-Build (RIBA, 2013b), the design team are able to incorporate in their design the complexity arising from the subcontractor's specific processes and capabilities.
- **Influence of early-stage design**: in product design, it is widely agreed that the initial stages of product development commit about 80% of costs, even if unknown (Asiedu & Gu, 1998; Miles & Swift, 1998; Namouz, Summers, & Mocko, 2012; Rehman & Guenov, 1998). In façades this is the fundamental stage where many costs are committed, especially as far as manufacturability is concerned (Voss & Overend, 2012).
- **Routine design and knowledge storage**: in product design, normal design activity consists of about 80% of routine tasks, whereas only the remaining 20% is spent for innovative design (Stokes, 2001). Part of the routine time is spent searching for information in personal databases (Baxter et al., 2007). During the façade design process, outcomes are stored in forms of meeting minutes and digital data in non-interactive formats such as .pdf /.docx /.dwg (Voss, 2013). Multiple requirements, ranging from building physics to structural design, logistics and manufacturing, require routine analyses to be repeated after a physical / geometrical feature of the façade is modified. These challenges are still present in the above-mentioned new forms of contractual arrangement (Design – Build, Integrated Project Delivery).
- **Lack / absence of (multi-objective) optimisation and predictive design:** the relatively small production batches in the building sector are such that computational optimisation is rarely used (Knowledge Transfer Network, 2016). A combined multi-objective optimisation that takes into account a certain number of constraints should be systematically used, given the high interdisciplinary nature of façade design. Research efforts in this sense appear to focus more on the optimisation aspect, rather than limiting the domain of solutions to what is manufacturable (Jin

& Overend, 2013). Predictive design through advanced and coupled performance modelling methods can increase the reliability of expected fa performance during the whole life-cycle.

## Existing tools supporting façade design

### Introduction and methodology

In façade design, the final design solution is developed through increased levels of complexity and detail. During this process, specific tools are used to support façade design tasks. A series of 2D and 3D drawing and modelling, visualisation and simulation packages support the development of sophisticated and technically complex systems and their interfaces. Physical models, mock ups and testing assemblies further support the development for the testing of visual and physical properties. In order to provide a comprehensive review, existing tools have been classified and mapped through the methodology shown in Table 1, following the criteria in Table 2. The total number of tools considered is 66. General-purpose tools (e.g. ABAQUS, Comsol, and Autocad) have been omitted for this classification.

Results are then represented in Gephi ver. 0.9.1 by Gephi Consortium, a graph theory-based tool for data visualisation. The graph presents nodes linked to each other and the whole diagram is analogous to an elastic system of interconnected springs. Nodes and links are given as an input and a specific algorithm places the nodes in space so that the system is in an equilibrium state corresponding to the minimum elastic energy in the links, thus forming clusters of nodes with similar characteristics, that is, similar links. The chosen algorithm is Force Atlas 2 (Jacomy, Venturini, Heymann, & Bastian, 2014), specifically developed by Gephi and frequently used for relatively small diagrams. Table 3 shows the parameters chosen for the simulation. For an enhanced visualisation of the map, an additional, interactive view (generated through the D3.js JavaScript library) can be also accessed at the following link (Glass and Façade Technology (gFT) Research Group, 2016).

### Results and discussion

Figure 3 shows the generated map. Nine distinct categories (green areas) are identified by the force-directed algorithm. Table 4 shows the main features of each category. Two main conclusions can be drawn, as follows:

- The majority of tools deal with one discipline only, rather than integrating multiple aspects concurrently. Figure 3 reveals that few 'tool' nodes (blue nodes) are linked to multiple and diverse 'design discipline' nodes (orange nodes). The only exceptions are tools in type A group which however correspond to the building physics domain (daylight, energy and comfort). There are few cases of multidisciplinary tools that connect nodes in different positions of the graph: in

**Table 1.** Methodology for classifying the reviewed tools supporting façade design.

| Step | Description |
|---|---|
| 1. Tool selection | Selection process based on: |
| | Authors' experience |
| | Discussions with the researchers withtin the Glass and façade Technology Research Group (gFT) and the Engineering Excellence Group in Laing O'Rourke |
| | Research on theInternet through combinations of keywords such as ('façade', 'curtain wall', 'cladding' OR 'panels') AND ('configurator', 'software' OR 'tool') AND ('glass', 'concrete', 'aluminium', 'steel' OR 'wood') |
| 2. Definition of classification criteria | See Table 2 |
| 3. Classification of tools | Each criterion (from step 2) was assigned to the selected tools (from step 1) |
| 4. Representation of results | Graph-theory-based tool Gephi ver. 0.9.1 through the Force Atlas 2 algorithm (Jacomy et al., 2014). See the algorithm's parameters in Table 3 |

**Table 2.** Classification criteria and related sub-criteria for classifying tools in façade design.

| Geometry manipulation | Design stage | Design discipline | Product-specificity |
|---|---|---|---|
| 1. 3D, including: | 1. Concept/Developed, including: | 1. Architectural design/design intent | 1. Product-specific: including data about one or more manufacturer-specific products |
| A. Tools that generate façade-specific components[a] | A. Tools for quick design of general dimensions of the façade (WWR, thickness, material selection) | 2. Structural[c] | 2. Non-product-specific: developed for generic façade applications |
| B. Tools that generate primitive 3D geometries | B. Tools for rapid sketching | 3. Thermal properties of a component (e.g. U-value of opaque walls) | |
| 2. 2D tools | C. Tools for selecting external finishes | 4. Visual properties of a component (e.g. t-vis of a glazed component) | |
| 3. No geometry manipulation | 2. Technical/Construction, including: | 5. Energy (e.g. dynamic energy simulation or simpler analyses) | |
| | A. Tools for supporting report generation / detailed analyses (e.g. FEM tools) | 6. Daylight (illuminance levels and glare risk) | |
| | B. Tools for shop drawing / detailed drawing generation | 7. Comfort (thermal comfort) | |
| | 3. All stages[b]: | 8. Order placement: tools that automatically place orders of façade systems / components | |
| | A. BIM platforms | 9. Manufacturing constraints | |
| | B. Dynamic Energy Simulation | 10. BIM | |
| | | 11. Cost | |
| | | 12. Logistics | |
| | | 13. Shop Drawings generation | |

[a]For example, a parametric grid of mullions and transoms for stick systems.
[b]This subcategory includes tools that can support every stage of the design process, due to their ability to deal with different levels of detail.
[c]No general-purpose tools have been included (e.g. FEM software like ABAQUS), but façade-specific tools only.

such cases, the node is not within any green area. An example is the Schueco Parametric System plugin, where architectural design is supported by manufacturability constraints and structural design.

- There is no tendency to bring late-stage design knowledge earlier in the design process. The graph in Figure 3 illustrates how categories of tools relate to the design stages. This could be inferred by the position of the categories with respect to the two red nodes (representing the conceptual/ developed and the technical/construction stages, respectively). It emerges that some categories of tools are only dedicated to later design stages, such as tools for generating shop drawing

**Table 3.** ForceAtlas2 (Jacomy et al., 2014) parameters for data representation.

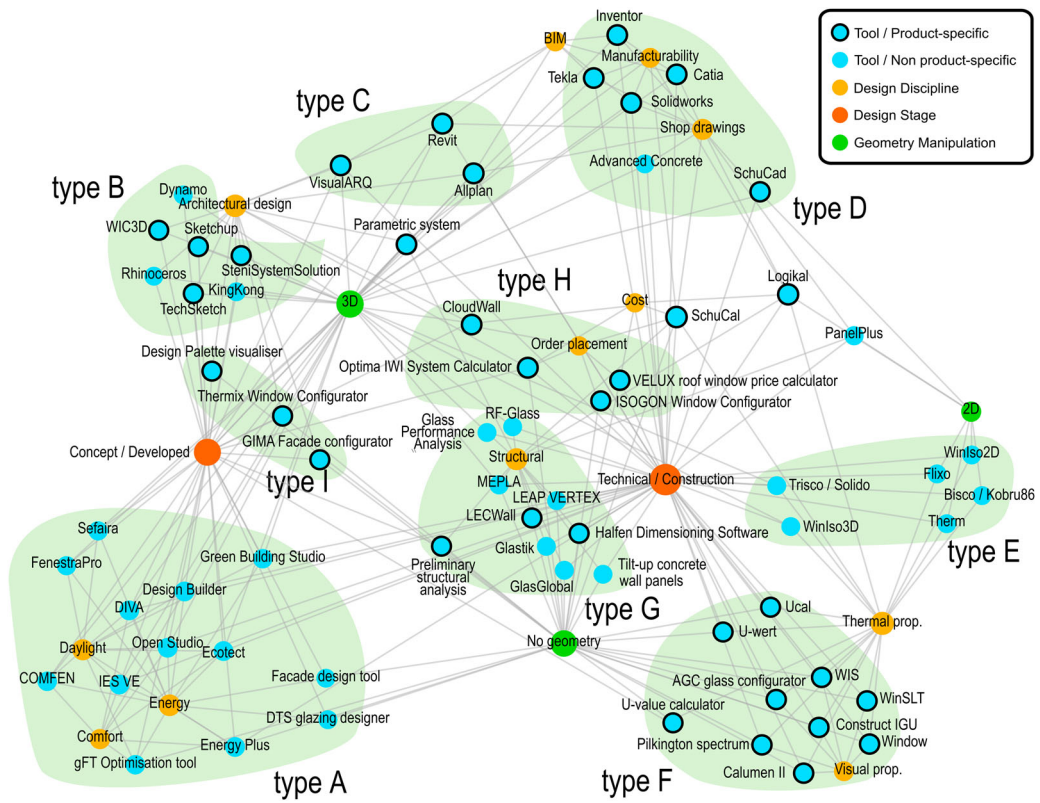| Parameter | Value |
|---|---|
| Threads number | 7 |
| Dissuade hubs | No |
| LinLog mode | Yes |
| Prevent overlap | No |
| Edge Weight influence | 1 |
| Scaling | 11 |
| Stronger gravity | No |
| Gravity | 1.5 |
| Tolerance (speed) | 1 |
| Approximate repulsion | No |
| Approximation | 1.2 |

**Figure 3.** Classification of tools supporting façade design: green areas represent the generated clusters of tools with similar functions.

(type D), 2D/3D thermal analyses (type E), thermal/visual properties of components (type F) and structural design (type G). Early design stages are mostly governed by type B category. Also, product-specific tools are mostly used in later design stages: blue nodes with a black outline are mostly orbiting around the Technical/Construction node.

The outcome of the graph shows how the currently available tools do not address the current design-manufacturability gap in the façade sector. There is no access to manufacturability knowledge early in the design stage and the integration between disciplines is not well supported. In general, façade subcontractors and system suppliers do not provide designers with tools that inform them on the implications of their choices on manufacturing issues and vice versa. There is therefore a need to overcome the traditional, partitioned approach of the construction industry when applied to façade design, with tools that allow designers to capture the complexity of façades in intuitive and informative ways.

## KBE in other industries and in the façade sector

### Introduction and methodology

Design automation through KBE is seen as a potential solution to increase quality and reduce delivery times and costs of Engineering-To-Order products (Willner et al., 2016). KBE systems have been successfully applied in the aerospace, automotive and shipbuilding industries. The first two industries are characterised by Make-To-Order (MTO)-type products, whereas shipbuilding typically involves ETO

**Table 4.** Description of the nine categories of tools resulting from the force-directed layout algorithm.

| Type | Name | Characteristics |
|---|---|---|
| A | Energy/comfort/daylight | • 3D whole building/room level dynamic thermal analyses<br>• Different degree of detail at different stages of the design process<br>• Template-based and non-product specific |
| B | Architectural design (non-BIM tools) | • Used for rapid 3D sketching in conceptual/developed stages<br>• IFC exporting capabilities, although not initially conceived for BIM<br>• Possibility to include product-specific components |
| C | Architectural design (BIM tools) | • Can model a 3D component and further detail it in later stages<br>• Can include product-specific data on cost and material properties.<br>• IFC exporting capabilities |
| D | Detailed drawing production | • Used in the final stage of design<br>• Libraries of standard components (product-specific)<br>• High level of 3D parametric manipulation.<br>• IFC exporting capabilities |
| E | 2D/3D thermal analyses | • FEM analyses for evaluating thermal bridges and condensation risk<br>• Used in later design stages<br>• Non -product-specific |
| F | Thermal/visual properties of components | • Highly product-specific<br>• Used in later design stages |
| G | Structural design | • Structural FEM analyses or local analyses models (strut-and-tie) for connections.<br>• Used in later design stages<br>• Can be product- or non-product specific |
| H | Online configuration | • To partially configure the product and required interaction with the manufacturer/supplier or<br>• Directly finalise the order online<br>• Product-specific<br>• 3D manipulation of tabular input |
| I | Online visualisation of the external appearance of products | • Providing a rendered image under different configurations and daylight levels<br>• Product-specific |

products. The present section reviews the application of KBE for both product types by analysing its application to the aerospace and shipbuilding industry. The methodology adopted in this study consists of a literature review and interviews with sector experts. Table 5 shows a comparison between the KBE applications reviewed in this study.

## Review

### Shipbuilding and aerospace design processes

*Shipbuilding design process*. Shipbuilding shares many common aspects with the construction industry: strict delivery time (Bronsart, Gau, Luckau, & Sucharowski, 2005; Bronsart, Wiegand, & Koch, 2005; Caracchi, Sriram, Semini, & Strandhagen, 2014), ETO products, low production batches (Semini et al., 2014). The two industries also operate in local and fluctuating markets (Pero, Stößlein, & Cigolini, 2015). The impact of services and equipment on the shipyard's created value, of around 70%, (Bronsart, Gau, et al., 2005), together with the large number of components from the supply chain (Solesvik, 2007), make internal and external collaboration of companies a fundamental factor in shipbuilding design (Semini et al., 2014; Tann & Shaw, 2007).

**Table 5.** Comparison between KBE applications in the shipbuilding, aerospace and AEC industries.

| Sector | Product type | Use of KBE | |
|---|---|---|---|
| | | Author | Description |
| Shipbuilding – Cargo ships | Engineer-to-order | Wu and Shaw (2011) | Rapid access to documents and knowledge on past projects |
| | | Elgh and Cederfeldt (2007) | Design optimisation heavy-welded components. Automatic generation of CAD drawings, process plans, bill of quantity |
| | | Cui et al. (2015) | Calculate trade-offs between weight and outer area of container ships, while complying with Classification Society's rules |
| | | Yang et al. (2012) | Automatic structural calculations and rule checking for designing a ship's hull |
| Aerospace | Make-to-order | La Rocca and Van Tooren (2007) | Early-stage multidisciplinary optimisation of whole aircraft |
| | | Feng et al. (2011) | Early-stage multidisciplinary optimisation of whole aircraft |
| | | Verhagen (2013) | Optimal ply stacking of composite aircraft wing |
| | | Emberey et al. (2007) | Fibre Metal Laminates panels design |
| | | Choi (2009) | Cost and weight assessment of composite components |
| | | Corallo et al. (2010) | Turbine and gearbox design |
| | | Stueber et al. (2009) | Multidisciplinary analyses and optimisation of aircrafts |
| Construction | Engineer-to-order | Gross (1996) | Rule-based program for modular design of building components |
| | | Ganeshan et al. (1996) | Generation of preliminary construction plans of US military facilities |
| | | Sandberg et al. (2008) | Stair configurator for prefabricated timber houses in Sweden |
| | | Aram (2015) | Knowledge-Based framework for quantity take-off (QTO) and cost estimation (CE) of precast products through the IFC schema |
| | | Karhu (1997) | Product Model of Façades to exchange information between stakeholders |
| | | Voss and Overend (2012) | Check façade manufacturing limits on a building scale |
| | | Said, Chalasani, and Logan (2017) | Exterior panelised walls platform optimisation (EPWPO) to configure wall systems (PWS), based on cost and on the deviation of the proposed design to a preferred design, and on detailed structural calculation |
| | | Fuchs et al. (2015) | Manufacturer-specific tool for early design of a unitised system |
| | | Zahner (2016) | Online configurator for cost calculation and order placement of external shadings |

Shipbuilding follows the typical sequential process of design stages (conceptual-preliminary-detailed). Traditionally, there was a clear separation between the design and manufacture of the hull structure and the outfitting (mechanical and electrical systems, finishes, etc.). This approach, despite allowing a better management of interfaces during the construction phase, could not keep pace with the demand for shorter delivery time (U.S. Department of Commerce, 1980). For this reason, interim products (U.S. Department of Commerce, 1980) were introduced: the overall ship is divided into modules characterised by their own work packages (hull and outfitting), materials and schedules (Tann & Shaw, 2007). Interim products are then assembled to form the final product. The introduction of interim products has therefore made logistics, such as crane and workstation capacities and transport restrictions, a new issue to be included in the early stages of design and integrated with the vehicle performance.

The contractual arrangement is another focal point in shipbuilding: the tender documentation, produced by the shipowner together with a naval architect, usually consists of general information with the purpose of obtaining an initial estimate from potential shipyards (Solesvik, 2007). The early appointment of the shipyard allows better management of logistics with subcontractor-specific knowledge supporting the design of the final product since the beginning. Integrated and collaborative approach, such as consortia between shipyard and subcontractors, provide a solution for reaching higher level of competitiveness and quality (Bronsart, Gau, et al., 2005).

*Aerospace design process*. The aerospace industry follows the traditional conceptual-preliminary-detailed process. The delivery process usually starts with a tender from an aircraft supplier or a military user that writes a set of specifications, based also on market research (Nicolai & Carichner, 2010). Bidders then evaluate a set of different solutions and develop the conceptual design and a cost estimation. Aircrafts can be classified as Make-To-Order products, since the order from the client ('decoupling point') is located between the design and manufacturing activity. The base product is usually modified in such a way that additional design activities are not required (e.g. hull's external colour, outfitting).

The main features of the airplane are determined at the conceptual stage and major design modification are not economically acceptable in later stages. Although cost modelling is used as a decision-making tool to guide the design team through the design process (Curran, 2005), the prominent issue is to meet design specifications as aerodynamics, propulsion and flight performance (Anderson, 1999).

During the preliminary design stage, structural and detailed CFD (Computational Fluid Dynamics) analyses are performed. At this stage minor modifications are allowed (Anderson, 1999); the final solution is then defined, or 'frozen' (Nicolai & Carichner, 2010), and delivered to the manufacturing facility.

The detailed stage converts aircraft design into shop drawings for production. Manufacturability aspects are mainly considered on a component level, for example, through Design for Manufacturing (Boothroyd, Dewhurst, & Knight, 2010) and no major modifications are allowed.

## Knowledge-Based Engineering

The purpose of KBE is to reduce the design effort through automation of repetitive tasks, knowledge reuse and to support product development in a multidisciplinary environment (Verhagen, Bermell-Garcia, Van Dijk, & Curran, 2012). KBE encapsulates various forms of knowledge such as heuristic knowledge, cost data, manufacturing best practices, rules-of-thumb and standards. KBE usually merges an object-oriented programming (OOP) approach and a parametric modelling software. The basic configuration of a KBE application is shown in Figure 4 (Reddy, Sridhar, & Rangadu, 2015).

The term 'KBE system' refers to general-purpose tools, whereas its actual implementation is called 'KBE application' (La Rocca, 2012). The core of a KB system is the Product Model, also called Meta-Model (Stokes, 2001). A Product Model represents a framework of interrelated concepts (e.g. engineering products, processes and the relevant knowledge) in a digital form, that models a specific
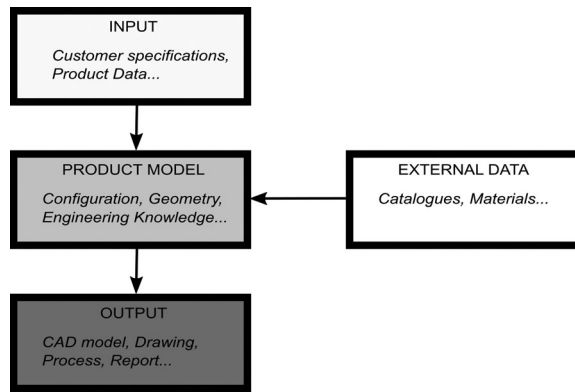
**Figure 4.** High-level view of a KBE system (Reddy et al., 2015).

domain of discourse. For this reason, a Product Model is also referred to as an Ontology (Uschold & Gruninger, 1996).

KBE systems were initially developed for aerospace and automotive industries. The first KBE systems dates back to the 1980s with the advent of the CAD-based tools ICAD (Sandberg, 2003) and Intent!. Examples of real-world cases of KBE are documented in Cooper, Fan, and Li (1999) for different types of design such as cockpits and wing ribs at Airbus, car body-in-white at British Steel or car headlamps at Jaguar. Although research still lacks a common metric for measuring the impact of KBE systems (La Rocca, 2012), some real-world applications in various domains have shown important achievements. Van Der Laan and Van Tooren (2005) showed an 80% saving in time to design the structure of the aircraft's movable parts; Kulon, Mynors, and Broomhead (2006) reduced the time for designing the manufacturing process of hot forging from weeks to hours; Chapman and Pinfold (2001) developed a tool for building the FEM mesh of a car body-in-white in few minutes, thus moving upstream, along the design process, a task which is usually considered in the post-design stage.

Specific methodologies exist for developing a KBE application: MOKA (Stokes, 2001), KOMPRESSA and KNOMAD (Verhagen, 2013). An overview of the above methodologies is provided in Reddy et al. (2015).

*KBE in shipbuilding and aerospace.* The design processes of these two industries share similarities in that vehicle performance is the key design driver during the early stages of design. The design of large cargo ships now involves subdividing the whole product in transportable and manufacturable sub-products, which emphasises the logistical aspect. Aerospace is more focussed on integrating different design aspects (such as aerodynamics, weight calculation and structural analyses) concurrently. Both industries also tend to bid early in the design process, thereby giving the potential contractors the possibility to guide design from early stages. In this way, the future manufacturing and assembly stages are more easily implemented.

The application of KBE to the examples in Table 5 shows that aerospace and shipbuilding industries are currently using KBE applications to deal with both the repetitiveness and the interdisciplinary requirements of their design tasks. The shipbuilding industry requires a careful definition of the initial main dimensions and form of the hull, propulsion characteristics, type of primary structure to achieve the required performances; since a wide range of expertise is required during early stages of design, KBE systems managing documents with knowledge on past projects is seen as a solution (Wu & Shaw, 2011). KBE is also used for automating part of the design process at component level for understanding costs in advance by introducing manufacturing criteria (Elgh & Cederfeldt, 2007) or on a whole-ship level to analyse trade-offs between the main features of the hull, while respecting a set of pre-established constraints, such as rules from the classification societies (Cui, Wang, & Shi, 2015; Yang,

Chen, Ma, & Wang, 2012). Similarly, the aerospace industry uses KBE applications to deal with inter-disciplinary and performance-related aspects during early stages of design on a whole-product level, such as weight and cost calculation, and structural and fluid-dynamics analyses (Feng, Luo, Liu, & Wu, 2011; La Rocca & Van Tooren, 2007; Stueber, Le, & Vrnak, 2009). KBE applications in aerospace are also used for automatic design of single components, such as optimising the ply-stacking sequence or assessing costs and weight of composite aircraft wings while considering manufacturing constraints, and assisting the design of aircraft turbines and gearboxes by generating 3D models for specific engineering analyses and by simulating the manufacturing process (Choi, 2009; Corallo, Margherita, Pascali, & Turrisi, 2010; Emberey et al., 2007; Verhagen, 2013).

*KBE in the construction industry and the façade sector*. In the AEC sector, KBE applications are still not a common practice. Many of the examples reviewed in this study (Aram, Eastman, & Sacks, 2014; Fuchs, Peters, Hans, & Möhring, 2015; Ganeshan, Stumpf, Chin, Liu, & Harrison, 1996; Gross, 1996; Karhu, 1997; Sandberg, Johnsson, & Larsson, 2008; Voss & Overend, 2012; Zahner, 2016) show an ad-hoc nature of the tools, rather than a framework for analysing multiple and conflicting performances, while constraining the governing variables. Most of these tools do not follow a specific rationale or methodology. In the façade sector, there are some recent initiatives of tools created by specific façade system suppliers and fabricators, such as the Schueco's Parametric System (Fuchs et al., 2015) and ShopFloor (Zahner, 2016). They demonstrate how providing designers with tools that capture limitations in their manufacturing and supply chain can play an important role in designing the final product, especially at early design stages.

The Building Information Modelling (BIM) approach and the Industry Foundation Classes (IFC) schema is the current approach for digitally supporting façade design. Objects containing information about geometrical features and material are exchanged through a standard file format. BIM supports digitalisation of information, whereas KBE supports digitalisation of knowledge: Figure 5 shows how the relationship between BIM and KBE is comparable to that between information and knowledge ('data in a context' *vs* 'ability to infer from information'). Isaac, Bock, and Stoliar (2016) used a clustering algorithm to explore both physical and functional interfaces between building components. Information was extracted automatically from an ifcXML file. Zhong et al. (2017), by using monitoring systems combined with Internet of Things (IoT), have created so-called smart construction objects (SCOs) that extend the information content of IFC-generated objects with the state during the design and construction process of prefabricated constructions. Nath, Attarzadeh, Tiong, Chidambaram, and Yu (2015) combined BIM parametric models of precast element and value stream mapping (VSM) for enhancing the production of shopdrawings. The benefits of a BIM approach are undeniable, such as reduced design times and errors; yet, the
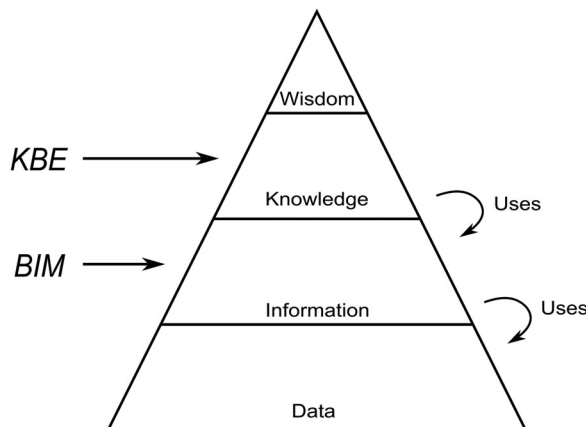


**Figure 5.** Relationship between information/knowledge and BIM/KBE.

absence of direct access to design & manufacturing knowledge and its integration, makes the user unable to make aware decisions.

The use of BIM for automatic rule checking of design, such as in Eastman, Lee, Jeong, and Lee (2009), presents an alternative rationale from KBE. In KBE, a Product Model is subjected to specific performance analyses to determine the optimal combination of physical and geometrical design variables: an IFC output can be then potentially generated. Rule checking, conversely, requires an existing model against which rules can be validated. The reviewed example of Aram (2015) for the façade sector is the most notable in this sense, in which knowledge about positioning rules of prefabricated concrete spandrels is acting directly on the model. Knowledge about positioning rules can also be transferred through a semantically enriched IFC file (Belsky, Sacks, & Brilakis, 2016). The challenge is to further enrich the IFC format with more complex rules and to support design by determining quantitative trade-offs between conflicting objectives.

## Discussion

From the above review, the following conclusions can be drawn:

- KBE is used for supporting design of ETO and MTO products. It has been shown that both the ship-building and aerospace industries use KBE to automate design tasks although they address different product types in terms of specification definition (shipbuilding = ETO / aerospace = MTO). Standard and reusable knowledge is usually embedded, with the benefit of integrating various sources of knowledge and reducing design times and errors.
- Aerospace and shipbuilding also show similarities with the construction industry in terms of engineering analyses between the whole component and its parts. In façades, a whole-building simulation is first used to define the façade's main features; the design then focuses on detailed analyses of sub-elements of the system (e.g. thermal analyses of joints). Similarly, in shipbuilding / aerospace, an overall assessment of performance is subsequently detailed to understand how subcomponents are manufactured and assembled. KBE is used in ship-building / aerospace both for early-stage, whole-product analyses and for late-stage, sub-component detailing.
- The façade sector has yet to adopt knowledge-based applications into the mainstream design routine. There is no obvious explanation for this finding, other than the relatively young age of the façade sector and the tendency to partition design tasks, which simultaneously increases the need for KBE, but makes it difficult to implement.

## Conclusions

The cross-disciplinary review undertaken in this study provides some useful insights into the future of digitally assisted façade design, which can be summarised in the following:

- The major challenges in façade design that should be overcome to unlock quicker delivery of façade product have been listed. It has been shown that, given the importance of early design stages, there is a need to bring later design criteria upstream in the process and include them in a digital form to create opportunities for early-stage optimisation. Understanding manufacturing constraints in the early stages of design is essential for achieving this.
- The review of current range of digital tools for supporting façade design shows focus on single disciplines and an inability to capture the highly interdependent nature of design. A partial, non-digital, coupling is currently achieved only through iterative checks between stakeholders during the design process. The majority of reviewed tools also do not support design in terms of understanding manufacturability aspects and including them into design, so that the

geometrical and physical features of the façade are carefully chosen and properly constrained. Some façade fabricators (Fuchs et al., 2015; Zahner, 2016) have recently started to include manufacturing constraints into ready-to-use digital tools.

- The façade and shipbuilding industries develop ETO products, while the aerospace industry is characterised by MTO/ATO products. The applications reviewed in this study show that KBE applications can be developed for both types, as long as there is standard and reusable knowledge associated to it. KBE can be applied either on a product-level or to subcomponents of the overall product. As an example, aerospace applies KBE to analyse the whole airplane as well as some of its parts, such as the optimal ply-stacking sequence of composite material in wings.
- The procurement forms of aerospace and shipbuilding engage the main contractor earlier in the design process, which supports the development of a solution from conceptual stages. The traditional procurement route in the construction industry, in which the design team develops a detailed solution to form the tender documentation, is being increasingly replaced by newer forms of procurement in which the contractor is appointed earlier in the process. This stimulates a more collaborative approach and shows similarities to the shipbuilding and aerospace industries. KBE applications can therefore support design digitally with company-specific knowledge and best practices, therefore addressing the 'manufacturing knowledge gap' in façade design.
- The façade industry has not fully adopted KBE, although there is a need to make reusable knowledge available to designers, especially capability in terms of manufacture and assembly processes and supply chain.
- KBE presents some fundamental differences with BIM. KBE focuses on the manipulation of geometry and physical attributes of a specific product, aimed at carrying specific analyses while applying knowledge under the form of rules and constraints. BIM manages the transfer of geometrical and physical information between platforms. Current research seeks to extend BIM capabilities by including simple rules.

The similarity with the shipbuilding and aerospace industries in terms of tasks to be solved and new procurement methods demonstrates that KBE can potentially fill the above-mentioned gaps in the current tools that support façade design. The façade supply chain can exploit the potential of these tools particularly during early stages, so designers are informed about how aesthetically similar design solutions can lead to different manufacturing costs (e.g. correct or wrong position of joints in prefabricated precast concrete façade panels or excessive dimensions of structural elements in glazed curtain wall systems) and service-life performances (e.g. condensation risks, overheating or glare risk).

The application of KBE to façades constitutes an opportunity to reduce the knowledge gap between the various stakeholders involved along the design and manufacture process of modern façades. Future work in this area requires the development of specific methodologies for building KBE tools in the façade industry, the creation of tailored use-cases for various procurement methods and stakeholders, as well as the establishment of performance indexes to evaluate the effectiveness of the digital tool.

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No potential conflict of interest was reported by the authors.

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