Digitised engineering knowledge for prefabricated façades

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Façade design is a multidisciplinary activity requiring the balancing of many conflicting design requirements. Very often, however, the designed façade does not respond to these requirement, as relevant design and manufacturing knowledge, normally originating downstream in the design process, is not properly used upstream in the process. The inability to respond to this challenge increases the environmental impact of the construction sector, which is currently covering nearly 40% of the global emissions. Also, improving the stagnant sector's productivity is of paramount importance today, as it is deemed to be nearly as half as that of the manufacturing sector. This research has thus investigated ways to collect, store, represent and digitalise the engineering knowledge that underpins the design of façade products for façades that are better designed. The work has involved a close collaboration with the British general contractor (and façade manufacturer) Laing O'Rourke. The research has explored ways of using design and manufacturing knowledge and it has developed a digital tool and tested its functionalities. In the first part, after a review of the state-of-the-art in knowledge-based approaches in other fields, the digital tool, and relevant methodology, are developed. The tool informs the user about the expected performance and manufacturability of the façade product under analysis. The boundaries of traditional research were also pushed beyond the proof-of-concept by validating the digital tool in both simulated and real-world scenarios. The goal was to understand how people can develop a design solution while being supported by a digital tool. It was found that using such tool increases the user's awareness about the consequences of the his/her choices in less time. In the last part of the research, the tool was used to develop a novel optimisation algorithm, by including considerations about aesthetics and manufacturability, in parallel with the traditional performance-based approach. The application of the algorithm to a case study has shown that it is possible to improve existing solutions in terms of performance, without affecting aesthetic and manufacturability significantly.

“puro e disposto a salire a le stelle.”
“pure and made apt for mounting to the stars.”

Dante Alighieri, Divine Comedy, Purgatorio, Canto XXXIII

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Declaration

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as specified in the text. It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text.

This dissertation does not exceed the prescribed word limit for the relevant Degree Committee. The full length is 34,735 words and it includes 61 figures and 15 tables.

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Nomenclature

AEC	Architecture, engineering and construction
API	Application programming interface
ATO	Assemble-to-order
BIM	Building information modelling
BPMN	Business process modelling and notation
CF	Constraint function
CNC	Computer numerical control
DB	Design-build
DBB	Design-bid-build
DFMA	Design for manufacturability and assembly
EIP	Explore Industrial Park
ETO	Engineer-to-order
GA	Genetic algorithm
GUI	Graphical user interface
IPD	Integrated project delivery
IT	Information technology
KB	Knowledge base
KBE	Knowledge-based engineering
MEP	Mechanical, electrical and plumbing
MTO	Modify-to-order
OOP	Object-oriented programming
PCSA	Pre-construction service agreement
PM	Product model
QTO	Quantity take-off
SME	Small medium entreprise
SV	Select-variant
TRL	Technology readiness level
UML	Unified modelling language
WCS	Weighted constraint score
WLV	Whole-life value
WTW	Window-to-wall ratio

Chapter 1

Introduction

1.1 Context

Façades are critical building elements that drive the quality, cost and aesthetical appearance of the final construction. From being secondary structural elements of separation between the internal and external environment, façades have become multifunctional elements that fulfil a wider range of performance. The recognition of façades as critical building elements, with their own design and performance-related criteria dates back to the first industrial revolution in the second half of the 19th century, when the quest for new forms in architecture introduced challenging applications of previously unexplored materials (Figure 1).

Figure 1: The Kew gardens, London

Materials such as steel, glass and concrete were produced in large quantities due to the advances in manufacturing techniques. Since then, architects and designers in the construction sector have pushed the use of those materials to the limit of their physical properties in more and more ambitious applications.

After world war II, the boom in population growth and the consequent environmental issues have put construction under the scrutiny of governmental policies. Prefabrication, with its mass-producing capability, came as a potential solution towards the increasing demand for more sustainable and affordable construction and it is still being used nowadays (Figure 2).

Figure 2: The recently-built Two Fifty One project in London (photo by courtesy of Laing O'Rourke plc)

Today façades must meet specific and stringent performance requirements, which partially arise from both national and international regulations and standards, and partially from clients' increasing expectations and aspirations. Façades must reduce operational energy consumption but provide, at the same time, comfortable internal environmental conditions; they must be manufactured and installed within budget and programme constraints but guarantee high quality standards and be built within strict tolerances; and, finally, they must be engineered while satisfying some kind of qualitative architectural expression which is realised in the designer's architectural intent.

The design process of façades includes a multitude of stakeholders, each one sharing different views and objectives, and therefore rarely working seamlessly towards a common goal. Moreover, stakeholders join the design team at different stages along the process, thus having less ability to influence other people's choice. Early-design stages, which are known to have a disproportionate effect on the final product cost, are normally driven by the architect's intent, which rarely considers the whole spectrum of performance- and manufacturing-related constraints into their design (upstream knowledge). This is caused, on the one hand, by the lack of information / knowledge (Appendix A) about manufacturing details of the façade from the future contractor (downstream knowledge), and, on the other hand, by the fact that façade design is only a fraction, however fundamental, of the building's overall design. Moreover, façade design is very sensitive to high-level (i.e. whole-building) decisions which determine unwanted intricacies at detailed level. For instance, the position of the horizontal joint in precast concrete panels, which is defined at a building scale by the panelisation scheme, can lead to structurally and thermally inefficient connections between the panel and the primary horizontal structure (Figure 3). The choice of the preferred window-to-wall ratio defines the length of the thermal bridges and the final U-value which, if not compliant with standards, must be corrected at a cost with additional insulation.

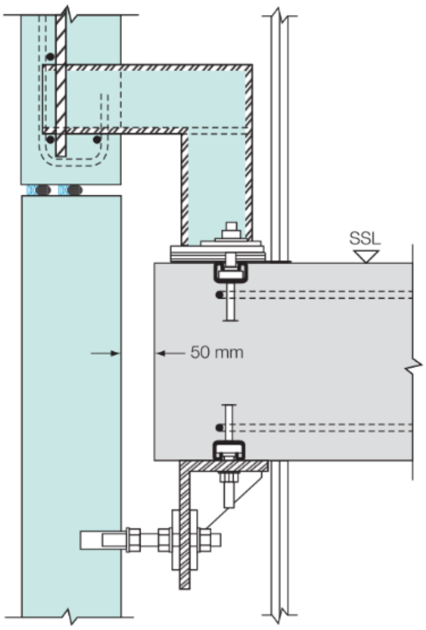


Figure 3: "Cranked" supporting bracket for precast elements, whose choice is driven by the exceedingly high position of the panel's horizontal joint with respect to the structural slab level (SSL) of the horizontal primary structure (figure by courtesy of Laing O'Rourke plc)

A more effective design and manufacturing process would require the integration of a larger amount of design criteria at earlier stages, even if the contractor/material supplier has yet to be appointed. This work aims to develop digital tools and relevant methodologies to tackle the issue of decision making in façades at early design stages. Before formulating the research questions, this chapter will first analyse further façades as products, their design processes and the state-of-the-art in terms of digital technologies for supporting façade design.

1.2 Background

1.2.1 Façades as products

The architecture, engineering and construction (AEC) sector is undergoing an increasing shift towards prefabrication to achieve higher environmental and quality standards, and to increase the productivity of the sector [1]. 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 [2]. As the involvement of the final client increases and architects are increasingly requiring high levels of bespokedness, prefabrication technology shifts to the so-called “flexible industrial prefabrication” [3], in which façades therefore become highly customised industrial products (although façades consist of a system of multiple sub-systems and products, we will refer to façades as “products” to allow for a general comparison with other industrial products).

Industrial products can be classified depending on the level of client involvement in the design, manufacture and assembly process (Figure 4), ranging from merely choosing between the alternative final products available (made-to-stock), to the increasing degrees of customisation (assemble-to-order / modify-to-order / engineer-to-order). Such products are defined by the position of the so-called “decoupling point” (DP) or “customer order penetration point” (COOP). The DP is the point, along the design, manufacture, assembly and delivery chain before which the client cannot exert their influence to change the company's operations. Façades are engineer-to-order (ETO) products, since each time a product is requested by the client, the delivery process starts from the design stage (i.e. DP at the beginning of the design stage).

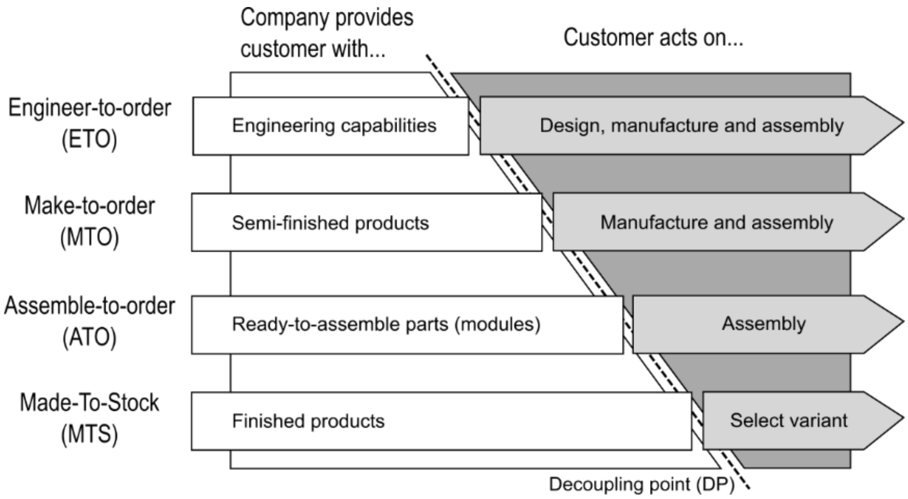


Figure 4: Classification of products depending on level of client involvement in the design, manufacture and delivery process (adapted from Hansen; 2003 and Rudberg & Wikner ; 2004)

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. pre-fabricated concrete panels), to the selection of standard systems (e.g. off-the-shelf curtain wall systems). A reduced level of bespokedness, e.g. 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 [6]. Product design is nowadays increasingly affected by how 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 [7].

1.2.2 Façade design as a 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 at a detailed level (e.g. 2D/3D finite element analyses of localised 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 5). 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 constraints [8]. A detailed, BPMN-based (business process modelling and notation) process map of a façade design process for a traditional procurement route has been developed by Voss et al. [9].

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 sub-contractors 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 (Appendix B), have been defined by the Royal Institute of British Architects [10].

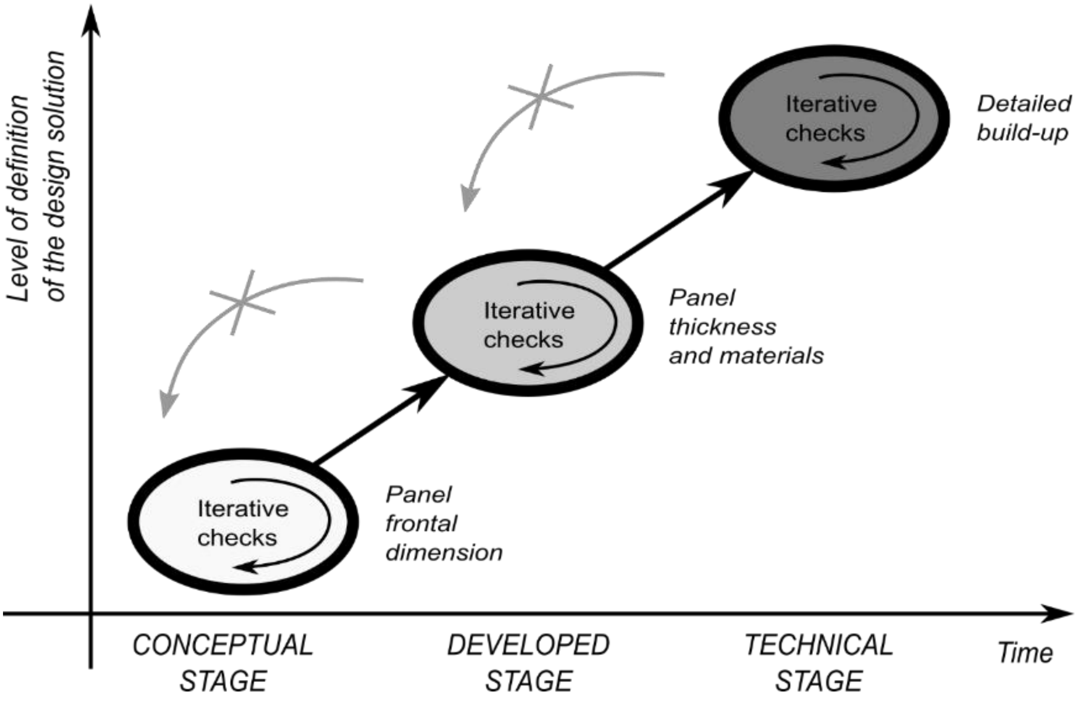


Figure 5: Schematic representation of the façade design process

Challenges in façade design

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 panelisation scheme (frontal dimensions), thickness and detailing of the internal build-up, while meeting production-related constraints [11] - Figure 5).
- 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 [12,13] coming from manufacturers [14]. In a traditional

delivery method, such as design-bid-build [15], different subcontractors informally support the design team before the tender stage [12,16]. In more integrated processes such as design-build [15], 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 [17–20]. In façades this is the fundamental stage where many costs are committed, especially as far as manufacturability is concerned [12].
- 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 on innovative design [21]. Part of the routine time is spent searching for information in personal databases [22]. 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 [23]. 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 also 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 is such that computational optimisation is rarely used [24]. The high interdisciplinary nature of façade design lends itself to a systematic use of a combined multi-objective optimisation that takes into account a certain number of constraints. Research efforts in this area appear to focus more on the optimisation aspect, rather than limiting the domain of solutions to what is manufacturable [25].

1.2.3 Digital tools currently used in 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 software 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.

Table 1: Methodology for classifying the reviewed tools supporting façade design

Step	Description
1. Tool selection	selection process based on: i. authors' experience ii. discussions with the researchers within the glass and façade technology research group (gFT) and the Engineering Excellence Group in Laing O'Rourke iii. research on the Internet through combinations of keywords such as "façade", "curtain wall", "cladding" or "panels" + "configurator", "software" or "tool" + "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 [26]. See the algorithm's parameters in

A comprehensive review of existing tools was performed during the course of this study through the methodology shown in Table 1, following the criteria in Table 2. The total number of tools considered was 66 (Appendix C). General purpose software (e.g. ABAQUS, Comsol, Autocad) have been omitted for this classification.

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. Tools for quick design of general dimensions of the façade (WWR, thickness, material selection)	2. Structural***	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**:	8. Order placement: tools that automatically place orders of façade systems / components	
	BIM platforms	9. Manufacturing constraints	
	Dynamic Energy Simulation	10. BIM	
		11. Cost	
		12. Logistics	
		13. Shop Drawings generation	

*: e.g. a parametric grid of mullions and transoms for stick systems

**: This subcategory includes tools that can support every stage of the design process, due to their ability to deal with different levels of detail

***: No general-purpose tools have been included (e.g. FEM software like ABAQUS), but façade-specific tools only.

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, i.e. similar links. The chosen algorithm is Force Atlas 2 [26], specifically developed by Gephi and frequently used for relatively small diagrams. Table 3 and Table 4 show the parameters chosen for the simulation. An enhanced visualisation of the map, including an additional, interactive view (generated through the D3.js JavaScript library) is available at the following link [27].

Table 3: ForceAtlas2 [26] numeric parameters for data representation

Threads num.	Edge Weight influence	Scaling	Gravity	Tolerance (speed)	Approximation
7	1	11	1.5	1	1.2

Table 4: ForceAtlas2 [26] Boolean parameters for data representation

LinLog mode	Prevent overlap	Stronger gravity	Approx. repulsion	Dissuade hubs
Yes	No	No	No	No

Results and Discussion

Figure 6 shows the generated map. Nine distinct categories (green areas) are identified by the force-directed algorithm. Table 5 shows the main features of each category.

Table 5: Description of the nine categories of tools resulting from the force-directed layout algorithm

Category type	**Category name**	**Characteristics**
A	Energy / comfort / daylight	3D whole building / room level dynamic thermal analyses different degree of detail at different stages of the design process template-based and non product specific
B	Architectural design (non-BIM tools)	used for rapid 3D sketching in conceptual / developed stages .ifc exporting capabilities, although not initially conceived for BIM Possibility to include product-specific components
C	Architectural design (BIM tools)	can model a 3D component and further detail it in later stages can include product-specific data on cost and material properties .ifc exporting capabilities
D	Detailed drawing production	used in the final stage of design libraries of standard components (product-specific) high level of 3D parametric manipulation .ifc exporting capabilities
E	2D/3D thermal analyses	FEM analyses for evaluating thermal bridges and condensation risk used in later design stages non product-specific
F	Thermal / visual properties of components	highly product-specific used in later design stages
G	Structural design	structural FEM analyses or local analyses models (strut-and-tie) for connections. used in later design stages can be product- or non-product specific
H	Online configuration	To partially configure the product and required interaction with the manufacturer / supplier or directly finalise the order online product-specific 3D manipulation of tabular input
I	Online visualisation of the external appearance of products	providing a rendered image under different configurations and daylight levels product-specific

Two main conclusions can be drawn:

- The majority of tools deal with one discipline only, rather than integrating multiple aspects concurrently. Figure 6 reveals that only a 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 are however limited to multiple discipline within 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 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.

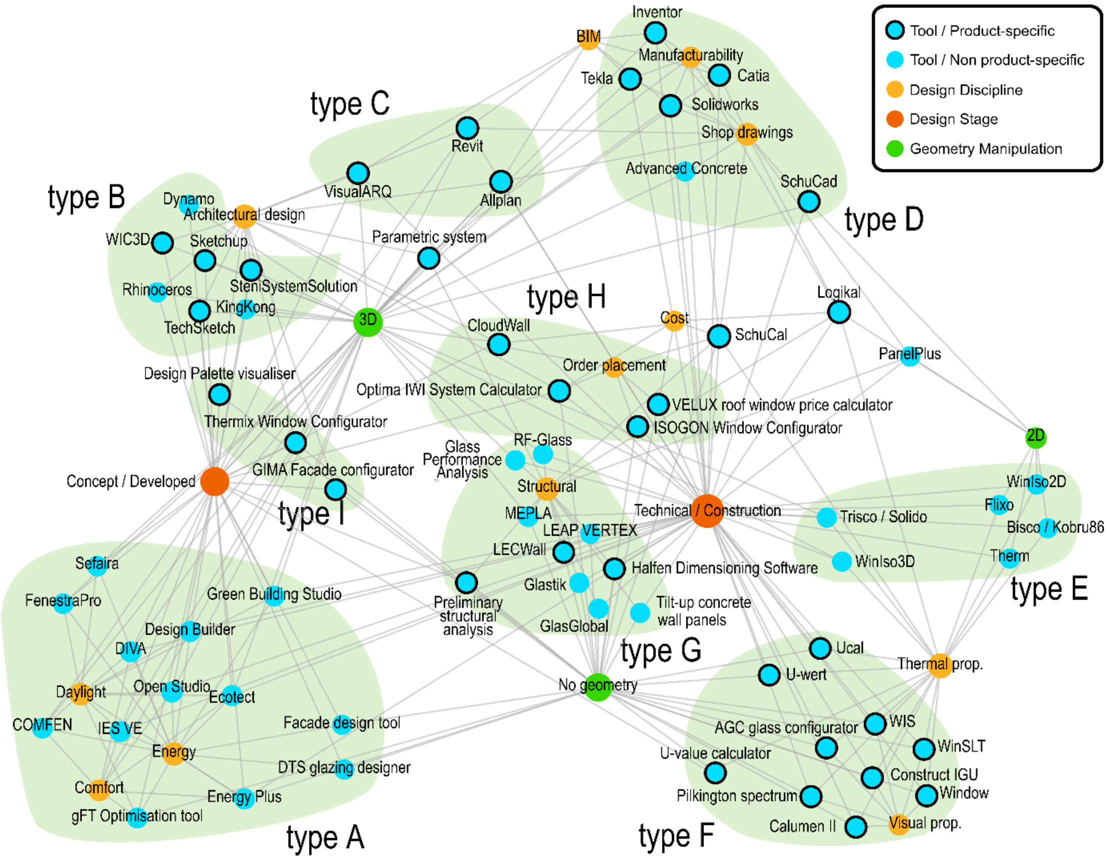


Figure 6: Classification of the investigated 66 tools supporting façade design: green areas represent the generated clusters of tools with similar functions

- There is no tendency to bring later-stage design knowledge earlier in the design process. The graph in Figure 6 illustrates how categories of tools relate to the design stages. This can be inferred by the position of the categories (second column in Table 5) 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 (D), 2D/3D thermal analyses (E), thermal /

visual properties of components (F) and structural design (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 mostly orbit around the Technical / Construction node.

The outcome of the graph shows that the tools that are currently available fail to address the current design-manufacturability gap in the façade sector (1.2.2). 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.

1.3 Research questions

Façades are engineer-to-order products that require early integration of a large number of design criteria. Their design includes several cross-disciplinary interdependencies, and manufacturing constraints that play a fundamental role. Design knowledge is dealt with on a project-by-project basis and is not properly stored. Repetitive, non-innovative design tasks cause exceedingly high productivity losses. Optimisation is still far from being fully utilised in the daily practice. Currently-available digital design tools do not address such challenges. Consequently, the present work will endeavour to answer the following overarch research question (RQ):

RQ: Can early-stage façade design be supported with digital tools that integrate multiple design & construction criteria?

To answer this question, a series of secondary research questions (SRQ) will be investigated:

SRQ1: What have other industries produced in terms of digital tools to support design?

SRQ2: What methodology should we adopt to develop digital tools to support design?

SRQ3: What would a proof-of-concept of a digital tool supporting design look like?

SRQ4: What are the validation strategies to evaluate the effectiveness of digital tools?

SRQ5: Can we improve façade design optimisation?

1.4 Structure of the manuscript

The thesis is subdivided into the following chapters, each addressing the above-mentioned research questions. Figure 7 shows a process-based view of the thesis in a BPMN [28] notation. All chapters include a brief, more detailed literature review which extends the general review made in this chapter, which has been used to address the research questions.

Chapter 1 has introduced the topic and laid the ground for the research questions to be addressed in the subsequent chapters.

Chapter 2 investigates and reviews the design processes and the approach currently adopted by other industries (namely, shipbuilding and aerospace) in the use of so-called Knowledge-Based Engineering (KBE) systems and applications to automatically support design.

Chapter 3 proposes a methodology for creating digital tools that support façade design, based on the current challenges and existing methodologies in other industries.

Chapter 4 demonstrates an application of the methodology to precast concrete (PCC) single-leaf panels manufactured in a specific facility in the UK (Explore Industrial Park (EIP) in Steetley).

Chapter 5 presents the outcomes of two field applications of the tool for its validation. In one case, a study is conducted with various façade consultancy companies to test how the tool can improve their design routine, whereas in the other the tool will be applied on two real-world projects to support the bidding stage of a façade contractor.

Chapter 6 proposes an approach that directly considers architectural intent as part of the optimisation problem.

Chapter 7 summarises the main outcomes from the preceding chapters and provides suggestions for future work.

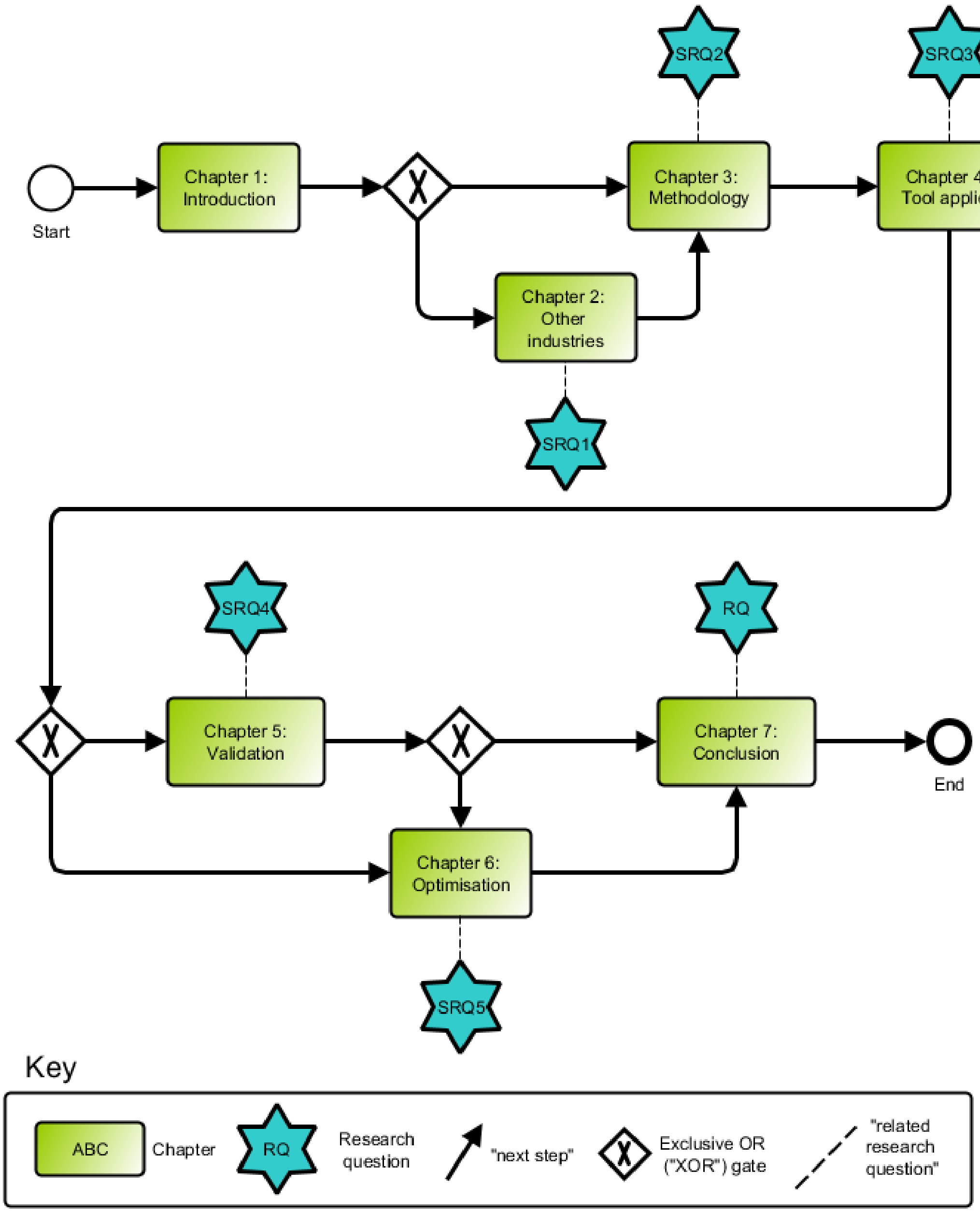


Figure 7: Process map of the manuscript in a BPMN [28] *view*

1.5 List of publications

The following publications were produced during this three-year PhD program:

<u>Journal publications</u>

Montali J., Overend M., Pelken P. M., Sauchelli M., Towards Façades as Make-To-Order Products – the Role of Knowledge-Based-Engineering to

Support Design. Journal of Façade Design and Engineering, v. 5, n. 2, p. 101-112, 2017.

Montali J., Overend M., Pelken P. M., Sauchelli M., Knowledge-Based Engineering in the Design for Manufacture of Prefabricated Façades: Current Gaps and Future Trends. Architectural Engineering and Design Management, v. 14, n. 2, p. 78-94, 2017

Montali, J., Sauchelli M., Jin Q. and Overend M., Knowledge-Rich Optimisation of Prefabricated Façades to Support Conceptual Design, Automation in Construction, v. 97, p 192-204, 2019

Conference publications

Montali J., Overend M., Pelken P. M., Sauchelli M., Towards Façades as Make-To-Order Products – the Role of Knowledge-Based-Engineering to Support Design. International Conference on Building Envelope Systems and Technologies (ICBEST), Istanbul, Turkey, May 2017

Montali J., Overend M., Pelken P.M., Sauchelli M., Knowledge-based Engineering Applications for Supporting the Design of Precast Concrete Façade Panels. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 6: Design Information and Knowledge, Vancouver, Canada, August 2017

Montali J., Overend M., Pelken P.M., Sauchelli M., Interactive Knowledge Bases to Support Façade Design – Knowledge Management Meets Data Visualisation, selected speaker at the Conference "ne-xt façades", Munich, Germany, November 2017

Chapter 2

Knowledge-based engineering in the shipbuilding, aerospace and AEC sectors

2.1 Introduction and methodology

The aerospace and shipbuilding industries have developed digital tools that support design through automation of reusable knowledge, known as knowledge-based engineering (KBE) systems. Design tools normally require the users to input their own knowledge; conversely, tools following a "knowledge-based" approach digitise and embed knowledge into the software application itself, thus resulting in an automatic and improved design support. KBE systems are represented by a product model (PM) [21] that includes various forms of knowledge from different engineering disciplines and combines them into a tool which captures their interrelationships. KBE is also seen as a potential solution to automatically support ETO product development [29]. 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.

KBE systems have been successfully applied in the aerospace and shipbuilding industries. The former is characterised by MTO-type products, whereas the latter typically involves ETO products. The present section reviews the application of KBE for both product types by considering its application to the aerospace and shipbuilding industry. The methodology adopted in this study consists of a literature review and interviews with sector experts.

2.2 Review

2.2.1 Shipbuilding and aerospace design processes

Shipbuilding design process

Shipbuilding shares many aspects with the construction industry: strict delivery time [30–32], ETO products, low production batches [33]. The two industries also operate in local and fluctuating markets [34]. The impact of purchased services and equipment on the shipyard's created value, of around 70%, [31], together with the large number of components from the supply chain [35], make internal and external collaboration of companies a fundamental factor in shipbuilding design [33,36].

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 [37]. For this reason, interim products [37] were introduced: the overall ship is divided into modules characterised by their own work packages (hull and outfitting), materials and schedules [36]. 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 ship's 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 for the purpose of obtaining an initial estimate from potential shipyards [35]. The early appointment of the shipyard is recommended because it allows better management of logistics with subcontractor-specific knowledge, thereby supporting the design of the final product from the early design stages. Integrated and collaborative approaches, such as consortia between shipyard and subcontractors, provide a solution for reaching higher level of competitiveness and quality [31].

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 [38]. Bidders then evaluate a set of different solutions and develop the conceptual design and a cost estimation. Aircraft can be classified as make-to-order products, since the order from the client (the “decoupling point”, section 1.2.1) is located between the design and manufacturing activity. A base product is usually designed and produced in such a way that additional custom features do not require re-design (e.g.: hull’s external colour, outfitting).

The main features of the aircraft 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 [39], the paramount issue is to meet design specifications such as aerodynamics, propulsion and flight performance [40].

During the preliminary design stage, structural and detailed CFD (Computational Fluid Dynamics) analyses are performed. At this stage minor modifications are possible [40]; the final design solution is then defined, or “frozen” [38], and delivered to the manufacturing facility.

The detailed stage converts aircraft design into shop drawings for production. Manufacturability aspects are mainly considered at a component level, e.g. through design for manufacturing and assembly (DFMA , Appendix B) [41] and no major modifications are allowed.

2.2.2 Knowledge-based engineering

Definition

The purpose of knowledge-based engineering is to reduce the design effort through automation of repetitive tasks, knowledge reuse and to support product development in a multidisciplinary environment [42]. 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.

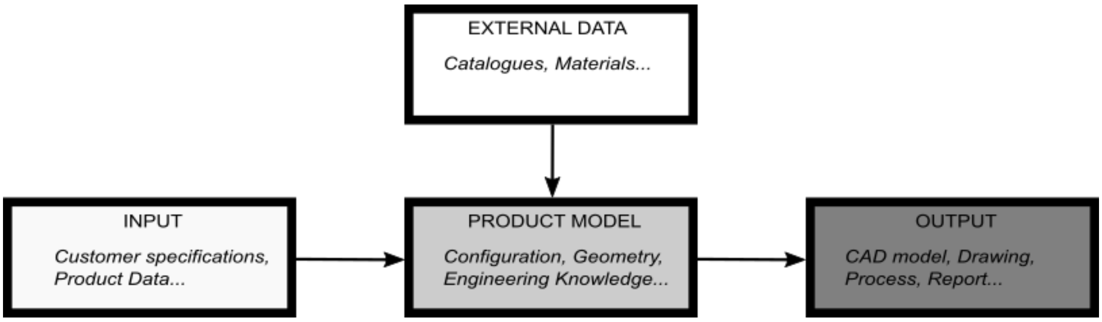


Figure 8: High-level view of a Knowledge Based Engineering system [43]

The term "KBE system" refers to general-purpose tools, whereas its actual implementation is called "KBE application" [44]. The core of a KB system is the product model, also called meta-model [21], as shown in Figure 8. A product model represents a framework of interrelated concepts (e.g. engineering products, processes and the relevant knowledge) in a digital form, that model a specific domain of discourse. For this reason, a product model is also referred to as an ontology [45]. The product model is linked to a material database containing the required information for the engineering calculations. The user normally inputs specific requirements via a graphical user interface (GUI) and receive a pre-specified output (such as drawings or reports).

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 [46] and "Intent!". Examples of real-world cases of KBE are documented in [47] 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 there is no broadly accepted metric for measuring the impact of KBE systems [44], some real-world applications in various domains have shown important achievements. Van Der Laan and Van Tooren [48] showed an 80% saving in time to design the structure of the aircraft's movable parts; Kulon et al. [49] reduced the time for designing the manufacturing process of hot forging from weeks to hours; Chapman and Pinfold [50] 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.

Methodologies for implementing KBE

Specific methodologies exist for developing a KBE application: MOKA [21], KOMPRESSA and KNOMAD [51]. These methodologies provide guidelines for transforming the initial available knowledge into a formal language to be subsequently implemented into a usable tool.

The first methodology to be developed was MOKA [21] (methodologies and tools oriented to knowledge-based engineering applications, Figure 9). The process consists of six steps: identify, justify, capture, formalise, package, activate. During the "capture" step, an "informal model" captures knowledge through "ICARE" forms, which represent different types of knowledge such as illustrations (experience from past projects), constraints, activities, rules and entities. A formal model is then built through a dedicated MOKA modelling language (MML). The "formal model" comprises a product model, where entities and constraints are included, and a "design process model", where rules and activities are reported. Although MOKA has been one of the most popular methodologies [52], different authors have highlighted its limits, such as the lack of: feedback iterations during the development process [53], a procedure to update the database and to validate the quality of the database [43,54], integration into the design process [42] and usable tools and relevant examples [54].

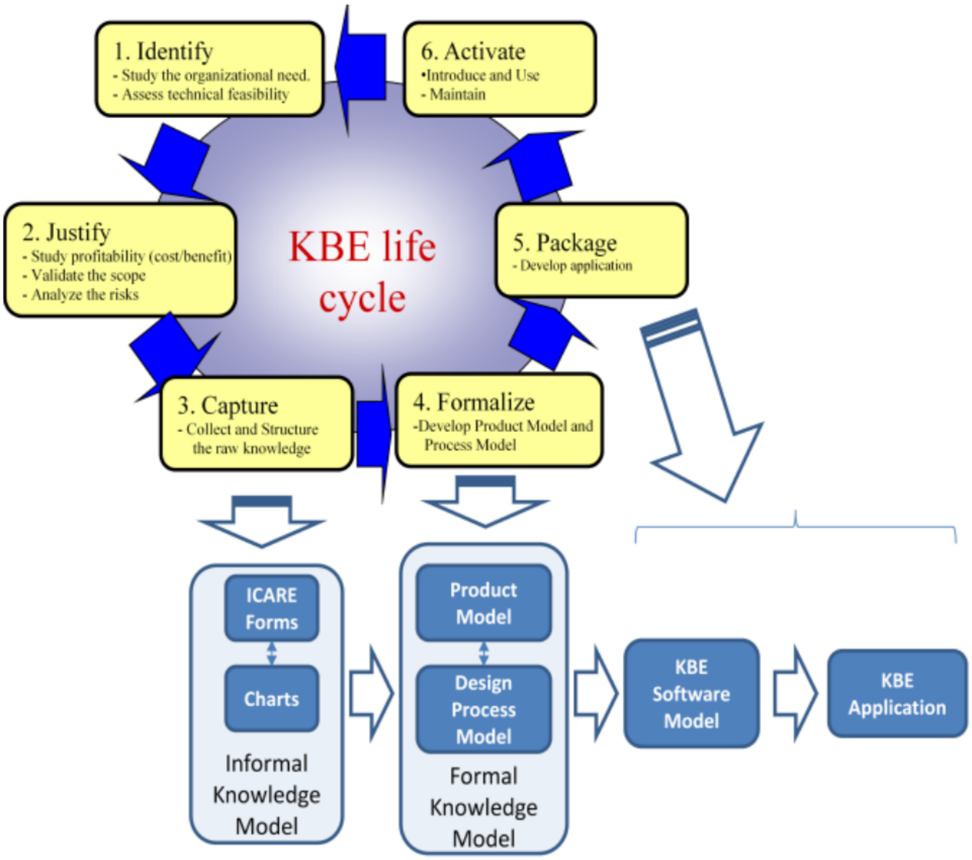


Figure 9: MOKA Framework [55]

KOMPRESSA (knowledge-oriented methodology for the planning and rapid engineering of small-scale applications) was specifically built for small medium enterprises (SMEs) and consists of a series of guidelines and graphical techniques for assisting the knowledge elicitation phase [56]. KOMPRESSA was developed in parallel with MOKA and the two share the same principles and shortcomings [52].

KNOMAD (knowledge nurture for optimal multidisciplinary analysis and design - [51]) was created for aerospace applications and it focuses on a multidisciplinary approach towards design. KNOMAD consists of six steps: knowledge capture, normalisation, organisation, modelling, analysis and delivery (Figure 10). The methodology also partially fills the gaps of MOKA and KOMPRESSA, by providing examples of implementation [57] and by validating the quality of the captured knowledge [54].

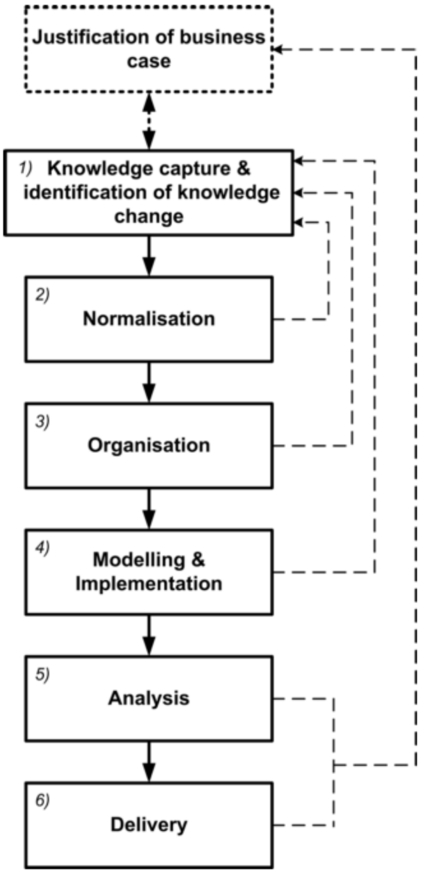


Figure 10: KNOMAD framework [51]

KNOMAD also considers knowledge maintenance by introducing the concept of knowledge life cycle [42], an object-oriented ontology that combines a product-process-resource (PPR) approach with the so-called “enterprise knowledge resource” ([58] - Figure 11), a system that keeps track of knowledge changes. KNOMAD uses the PPR approach to model the three main components of a production system as uniform and interconnected entities. Products are defined as either parts, assembly of parts or joints; assemblies are made from parts and/or joints. The enterprise knowledge resource manages the process view (i.e. the history) of how knowledge changes and the use of the KB application via the “cases” class, which are seen as a resource.

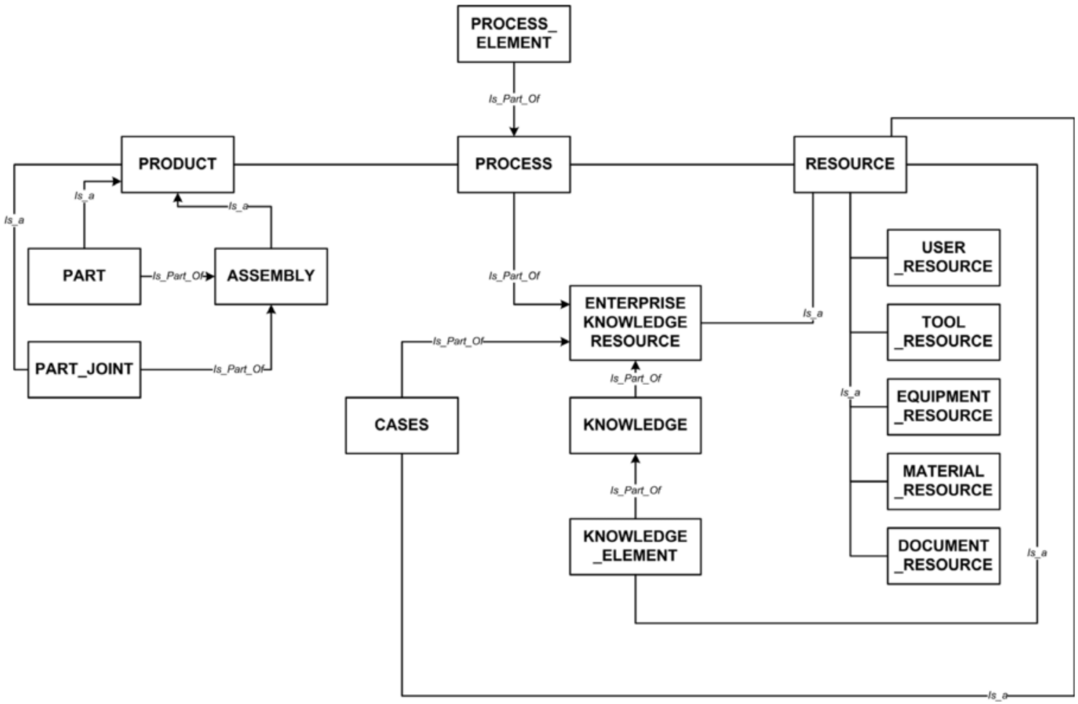


Figure 11: Product-Process-Resource model ontology in KNOMAD [51]

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, 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 in aerospace and shipbuilding is summarised in Table 6. This 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 [59].

Table 6: Reviewed KBE applications in the shipbuilding, aerospace, and AEC industries

Sector	**Product type**	**Use of KBE**	
		Author	**Description**
Shipbuilding - Cargo ships	Engineer-to-order	Wu & Shaw [59]	Rapid access to documents and knowledge on past projects
		Elgh & Cederfeld [60]	Design optimisation heavy-welded components. Automatic generation of CAD drawings, process plans, bill of quantity
		Cui et al. [62]	Calculate trade-offs between weight and outer area of container ships, while complying with Classification Society's rules
		Yang et al. [61]	Automatic structural calculations and rule checking for designing a ship's hull
Aerospace	Make-to-order	La Rocca & Van Tooren [57]	Early stage multidisciplinary optimisation of whole aircraft
		Feng et al. [64]	Early stage multidisciplinary optimisation of whole aircraft
		Verhagen [51]	Optimal ply stacking of composite aircraft wing
		Emberey et al. [66]	Fibre Metal Laminates panels design
		Choi [65]	Cost and weight assessment of composite components
		Corallo et al. [67]	Turbine and gearbox design
		Stueber et al. [63]	Multidisciplinary analyses and optimisation of aircrafts
Construction	Engineer-to-order	Gross [68]	Rule-based program for modular design of building components
		Ganeshan et al. [69]	Generation of preliminary construction plans of US military facilities
		Sandberg et al. [70]	Stair configurator for prefabricated timber houses in Sweden
		Aram [71]	Knowledge-Based framework for quantity take-off (QTO) and cost estimation (CE) of precast products through the IFC schema
		Karhu [72]	product model of Façades to exchange information between stakeholders
		Fuchs et al. [74]	Manufacturer-specific tool for early design of a unitised system
		Zahner [75]	Online configurator for cost calculation and order placement of external shadings
		Voss & Overend [12]	Check façade manufacturing limits on a building scale
		Said et al. [73]	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

KBE is also used for automating part of the design process at component level for quantifying costs in advance by introducing manufacturing criteria [60] 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 [61,62]. Similarly, the aerospace industry uses KBE applications to deal with interdisciplinary 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 [57,63,64]. KBE applications in aerospace are also used to design 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 [51,65–67].

KBE in the Construction Industry and the Façade Sector

KBE applications are still not common practice in the AEC sector. Many of the examples reviewed in this study 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 emphasise the final digital application, rather than the creation process. Gross [68] developed an application to design building floorplans based on a pre-established grid and positioning rules for the main building elements, such as infill walls, structural and mechanical, electrical and plumbing (MEP) systems. The application interprets design as the assembly of modular products similar to a “LEGO” construction. Ganeshan et al. [69] used a rule-based approach to support the generation of military facilities in the US at preliminary stage. The application generates design options to a level of detail that allows the early assessment of construction schedules and costs. Sandberg et al. [70] developed a stair configurator for prefabricated timber houses for instantaneous use with clients. The authors used MOKA ICARE forms to collect and store knowledge. Aram [71] developed a framework for the use of BIM and domain knowledge for assessing costs and quantity take-off (QTO) of precast concrete elements. The framework consists of four layers: a domain layer, where cost-specific knowledge is stored, a reasoning layer, where the ontological framework and rules are included, a task layer, where the required outputs are calculated based on the inputs, and an interface layer for the interaction between the user and the digital system. Karhu [72] created a highly object-oriented (in the EXPRESS-G visual representation language and implemented in LISP – LISt Processing) digital product model of precast façades that allows to store and output the main façade's features (such as dimensions and positions of the layers, joint types, reinforcement bars). Said et al. [73] developed a digital application to automatically optimise and design a specific wall system named "panelised walls systems" (PWS) in terms of cost and an index that takes into account for the deviation from the original design requirements. Voss & Overend [12] developed a tool to assess the manufacturability of façades by querying an IFC (industry foundation classes) file to determine, for instance, maximum/minimum panel dimensions, aspect ratio and maximum curvature for cold-bent glass.

There are also some recent tools created by specific façade system suppliers and fabricators. These tools demonstrate how providing designers with digital 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 Schueco's "parametric system" [74] is a plugin for Grasshopper / Rhinoceros that allows designers to parametrically configure a specific unitised façade system supplied by Schueco. Design knowledge is embedded in terms of structural analysis of the mullions, as well as ability to generate a highly detailed solution that is compliant, in terms of manufacturing constraints, to computer numerical control (CNC) machines for production (Figure 12).

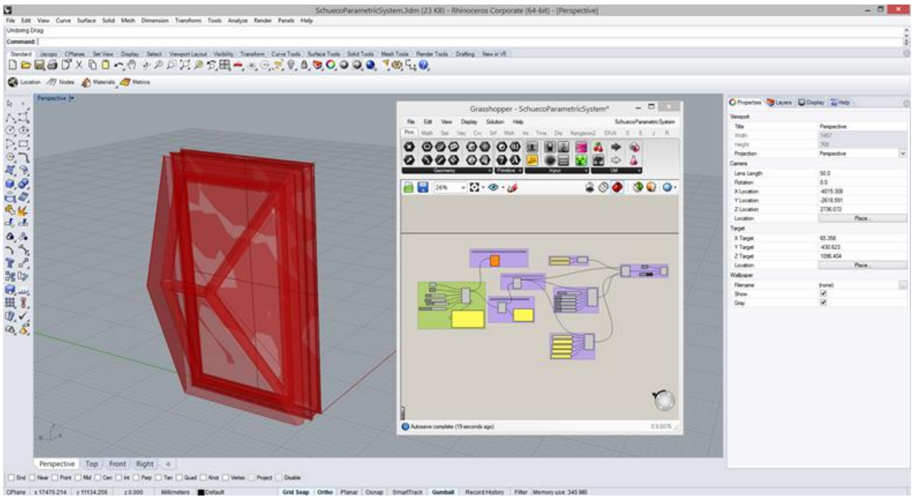
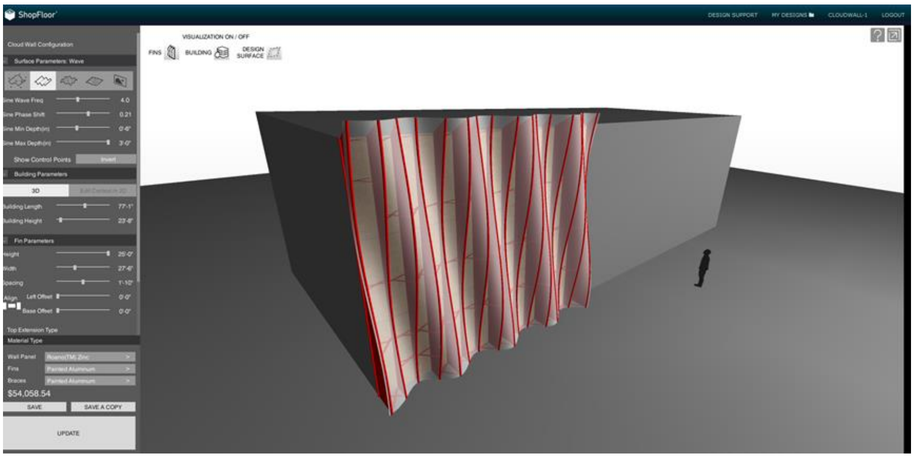


Figure 12: Schueco's Parametric System [74]

ShopFloor [75] is an online platform whereby users can configure an external shading system made from vertical steel fins. The platform has slides to parametrically select a variety of configurations. A cost estimate is immediately returned to the user, and the selected configuration is ready for production.



Cloud Wall Configuration

Surface Parameters: Wave

ine Wave Freq 4.0

ine Phase Shift 0.21

ine Min Depth(in) 0'-6"

ine Max Depth(in) 3'-0"

Building Parameters

uilding Length 77'-1"

uilding Height 23'-8"

Fin Parameters

eight 25'-0"

idth 27'-6"

pacing 1'-10"

Left Offset 0'-0"

Base Offset 0'-0"

Material Type

Wall Panel RoancoTM Zinc

Fins Painted Aluminum

Braces Painted Aluminum

$54,058.54

Figure 13: ShopFloor [75]

The building information modelling (BIM) approach with the IFC information exchange 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 6 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 et al. [76] 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. [77], by using monitoring systems combined with Internet of Things (IoT), have created so-called "smart construction objects" (SCO) that extend the information content of .ifc-generated objects with the state during the design and construction process of prefabricated constructions. Nath et al. [78] combined BIM parametric models of precast element and value stream mapping (VSM) for enhancing the production of shop drawings. The benefits of a BIM approach are undeniable, such as reduced design times and errors; yet, the absence of direct access to design & manufacturing knowledge and its integration make the user unable to make aware decision.

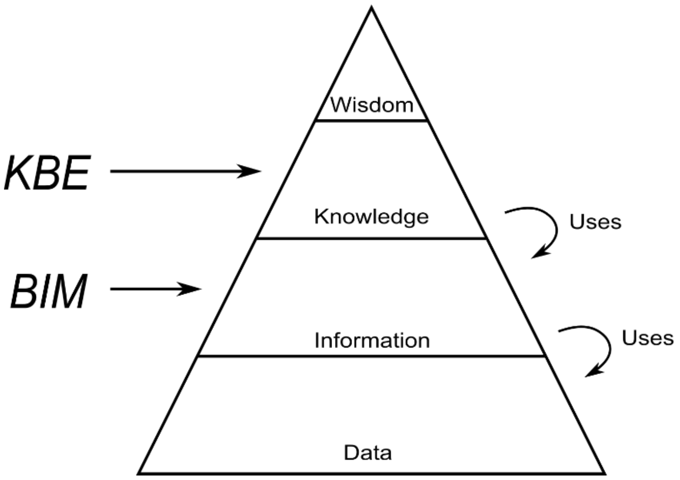


Figure 14: Relationship between information / knowledge and BIM / KBE

The use of BIM for automatic rule checking of design, such as in [79] 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 [80] 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 [81]. 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.

2.3 Conclusion

From the above review and based on SRQ1 (chapter 1), the following conclusions can be drawn:

- KBE is used for supporting design of ETO and MTO products. It has been shown that both the shipbuilding 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 shipbuilding / 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 as demonstrated from the few digital applications reviewed. There is no obvious explanation for this finding, other than the façade sector has only recently become a discipline in its own right and façade complexity has increased very significantly over the last 20 years.

- 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. Section 1.2.2 has described the traditional procurement route in the construction industry, in which the design team develops a detailed solution to form the tender documentation, and how forms of procurement are being increasingly replaced by newer ones 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. Knowledge-based engineering applications can therefore support design digitally with company-specific knowledge and best practices, therefore addressing the "manufacturing knowledge gap" in façade design.
- KBE presents some fundamental differences with BIM. KBE focuses on the manipulation of geometry and physical attributes of a specific product, aimed at performing 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 / incorrect 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 next chapter investigates a methodology for the creation of such digital applications in the façade sector.

Chapter 3

A methodology towards digitally-supported façade design

3.1 Introduction

Digital technologies supporting façade design are currently limited to applications that analyse single problem domains and do not capture the interrelationships between design criteria and the façade's physical features and governing parameters. By controlling the product model, knowledge-based engineering applications perform multiple engineering calculations and compliance checks simultaneously. Most real-world applications of KBE involve aerospace and shipbuilding industries. Standard methodologies have been developed to create KBE applications: MOKA was the first and provided standard forms ("ICARE") for knowledge collection, whereas KNOMAD is the most recent and partially offsets the drawbacks of previous methodologies (section 2.2.2).

The possible application of the KNOMAD methodology to façade design can be evaluated by a SWOT (strengths, weaknesses, opportunities, threats) analysis shown in Table 7. This reveals that, although there is an opportunity to apply it to the façade sector (chapter 2), the methodology was never been applied for the analysis of façade products/systems before. Also, although the methodology provides a broad and general framework with detailed aspects of knowledge management (e.g.: knowledge change), it can be seen as exceedingly complicated for experts in the façade sector, whose main focus is on the analysis of the product architecture and its underlying design & manufacturing knowledge. These aspects can be seen as the main limitations towards the application of the methodology in the façade sector.

Table 7: SWOT analysis of the use of the KNOMAD methodology for digital tools development in façades

	Helpful	**Harmful**
	Strengths	**Weaknesses**
Internal origin	Deals with knowledge change	Façade product architecture not included
	Examples of implementation available	Very elaborate
	Opportunities	**Threats**
External origin	Novel to the façade sector	Sector experts might be reluctant to adopt it

For these reasons, the present chapter will first set a theoretical basis (section 3.2) to target the above weaknesses for the application to the façade sector. After reviewing the concept of façade "product architecture" (section 3.2.1) from literature, it will be shown how product architecture can be digitally implemented via object orientation and abstraction techniques (section 3.2.2). Then, the chapter will set out the step-by-step process of the proposed methodology for creating and implementing the product model into a digital application (section 3.3).

3.2 Façade product architecture, and object-orientation and abstraction

3.2.1 Product architecture in façades

The widely accepted definition of product architecture is provided in a popular paper by Ulrich [82], who defines it as:

> *"(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components."*

where the “functional elements” describe the physical component’s function (normally in the form of natural language, such as “provide thermal insulation”). The product architecture is therefore determined by a three-step process. Firstly, by listing the functions (or “functional requirements” as per Suh [83]) that the product is expected to fulfil; secondly, by assigning these functions to the physical components. If there’s a one-to-one mapping between physical components and functional elements (i.e.: no function is shared between two components), then the product architecture is defined as “modular”, otherwise it will be referred to as “integral”. This step therefore requires all components and their function to be listed and their interrelations to be understood. The third step involves analyses of the interfaces to distinguish between three different types of modular architecture: sectional, slot or bus (Figure 15). In a modular “sectional” architecture, the interfaces between all components are identical. A “slot” modular architecture presents different interfaces (e.g.: in terms of geometry) between all connected components; a “bus” architecture type has all the physical components connected to a main component (the “bus”) through the same interface. Three examples of such products are a laptop and its physical components, the USB port and the connected devices (the laptop acting as a bus), and a construction made from bricks, respectively. Integral products show either unclear interfaces between components or so-called “coupled” interfaces, such that the change in one component requires a change in the another. Coupled interfaces are not present in modular products.

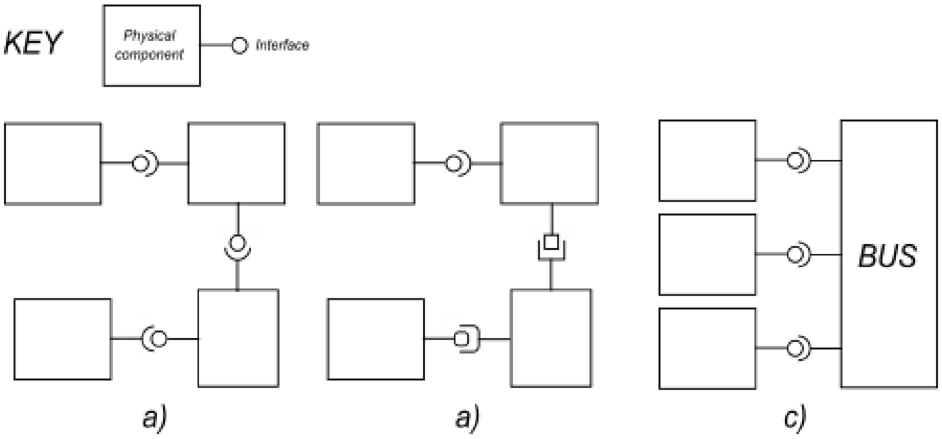


Figure 15: Schematic representation of a) sectional, b) slot and c) bus modular architecture

The concept of product architecture for façades has been studied by Klein [84]. The "façade function tree" lists the possible functions performed by a façade product to different levels of granularity, from *main functions* and *primary* and *secondary* functions, to the *detailed* and *detailed supporting* functions. Physical components are further classified and categorised in the so-called "façade product levels" (Table 8). *Product levels* represent classes for the taxonomy of a product, from the high-level product as a whole (the building), to the basic, single components (materials). *Commercial materials* differ from *standard materials* in that the former are manufactured for a specific project or product, whereas the latter are standard and normally manufactured by multiple companies.

Table 8: Façade product levels [84]

Product level	**Example**
Material	Steel / concrete
Standard material	Standardised I beam
Commercial material	Extruded steel profile
Element	Insulated glazing unit
Sub component	Window / Precast concrete
Component	Unitised façade piece
Building part	Curtain wall
Building	Building

The constructional analysis proposed by Klein aims to describe the façade product architecture by proposing a six-steps process that includes: 1) data collection, 2) extraction of the product functions from the "façade function tree", 3) mapping the physical components to their functions, 4) categorisation of physical components in accordance to the *product levels*, 5) interface analysis and 6) final analysis.

The approach proposed by Klein conceptualises the façade product into its essential[1] features: a façade product is such if its physical components perform specific functions and interfaces show a specific relationship, in accordance with a pre-built taxonomy and function tree. The built ontological framework thus determines *what the product really is*. If two products share the same outcomes at step 6, then they can be considered identical (or as belonging to the same *class*, see section 3.2.2). This introduces a higher level of abstraction of the product, in which the product is not only its material components, or its functions but *the mapping* between its functions and its components, and the type of its interfaces. Hence products with the same components and functions but different mapping are different. For example, load-bearing and non load-bearing single-skin concrete façade panels consist of the same components (e.g. externally-facing layer, concrete layer, insulation layer, structural connections) and functions (e.g. transfer self-weight to primary structure); however, the mapping (in this instance the load path) is different as in the load-bearing case the concrete leaf transfers its self-weight directly to the component below (or the foundation), whereas in the non load-bearing case the self-weight is transferred by the structural connection (normally consisting of a steel bracket) to the structural slab.

This approach will be used as a basis for the proposed methodology and is demonstrated in the case study of a precast concrete panels (chapter 4) to build digital tools that automatically support façade design. Section 3.3 describes in detail which parts of the method have been used and how the approach has been extended to manage design & manufacturing knowledge.

3.2.2 Object orientation and abstraction

Object orientation refers to a computer programming paradigm which is governed by *objects*. In object-oriented programming (OOP), *objects* model

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[1] We use here the concept of "essence" by referring to the tautological definition normally used in philosophy: what makes something be what it is.

entities of reality or the phenomenon under investigation. Those entities can be physical components of a product, its functions, processes, people or in general anything that exists[2]. An *object* is generated from or, equivalently, is an instance of, a *class*. A *class* is a high-level representation of a set of *objects* that share the same properties and behaviour. A *class* is therefore identified by specific properties and behaviours. A property can be the fact that, for instance, a unitised façade has a height, weight or a U-value. The behaviour of an object expresses the ability to change its state (e.g.: for a unitised façade, changing the type of glass or the height). Properties are normally represented by a number, a string, or boolean variables[3] and therefore they (can) take values whenever an object is instantiated from a class. Behaviour is instead represented by functions (in programming terms, not in Klein's or Ulrich's terms). An example of the relation between classes and objects is shown in Figure 16 .

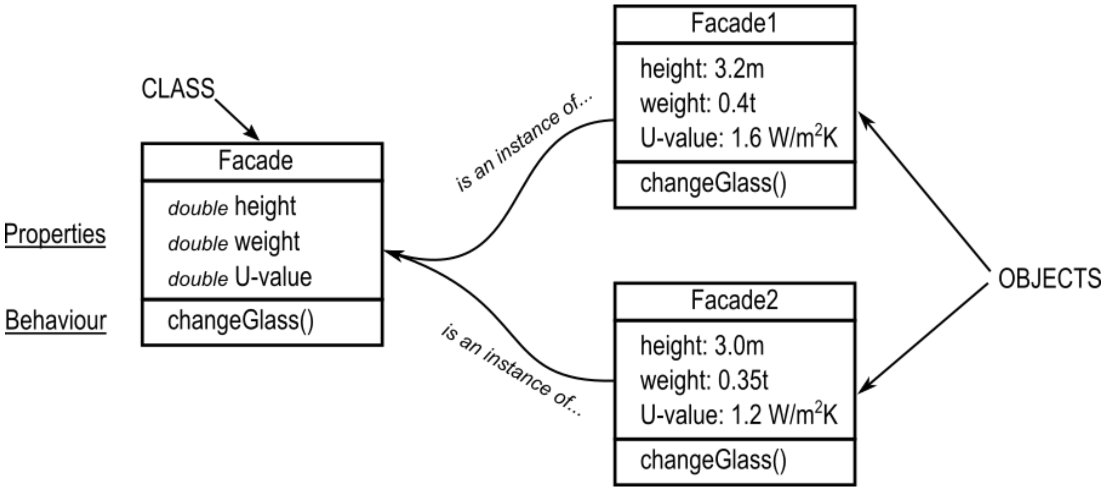

Figure 16: Example of a class representing a façade and two instances (objects) in a simplified UML [86] representation

In Figure 16, the "Façade" *class* (on the left) represents all the *objects* that have a height, a weight, a U-value and that can change the glass (one might argue that these features are insufficient to describe a façade, but this is just an

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[2] Greek philosopher Parmenides would say "nothing comes from nothing", although it is still possible, in OOP, to model a "null" entity.

[3] A property type can also be represented by another *class*. As an example, a "Window" *class* can have a property represented by a "Glass" *class*.

example). The "Façade1" and "Façade2" *objects* are instances of the "Façade" *class* in that they are generated from "Façade" *class* and give specific values (in the example: double-precision numbers) to the *class*' properties.

Creating classes that represent entities is therefore equivalent to answering the following question: "What is it that makes that entity what it really is?". It is possible to answer this question by introducing the concept of abstraction. Abstracting means removing all unnecessary features of a phenomenon, physical entity or product, until what remains is sufficient to describe it. In OOP, abstraction means creating classes that have the minimum sufficient number of properties and behaviours to describe a physical or imaginary entity. The following section will expand further on abstraction in façades and it will incorporate the aforementioned concept of product architecture.

3.2.3 Discussion on product architecture and abstraction in OOP

There is an intimate link between product architecture and OOP. Product architecture represents an entity in terms of its physical components, functions, interfaces and their mapping, whereas OOP is a programming technique for representing real-world (or even imaginary) entities through, amongst others, a strategy named abstraction.

A methodology that aims to develop digital tools should consider both approaches concurrently. Both techniques, in fact, provide the skeletal structure above which design & manufacturing knowledge will be applied: the former in a conceptual, product-oriented form, the latter for the actual programming, "hands on" implementation. The former lays the ground for the latter.

Removing detailed features from the product architecture reduces the burden associated with the implementation into programming code. This also equates to studying the product architecture at a higher level. Also, very high levels of abstraction might lead to more generality and broader applicability of the same product model (section 2) on multiple projects. It is in fact very important to consider the reusability of the PM since façades are engineer-to-order (ETO) products: it might not be possible to produce a new, highly detailed (hence lowly abstracted) PM on a project-by-project basis. However, there is a trade-off between the level of detail represented in the model and its ability to be usable. PMs that are too abstract run the risk of being unused, whereas PMs which are too detailed can be overly expensive to implement and maintain.

3.3 The proposed methodology

3.3.1 Overview

The proposed methodology takes the concepts of product architecture and OOP and integrates them into an iterative process that includes the collection of domain-specific design & manufacturing knowledge (Figure 17). It consists of four main steps that incrementally increase the formality of the captured knowledge, from high level to low level. The methodology contains the typical features of KBE methodologies such as MOKA and KNOMAD, e.g. 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 multidisciplinary criteria.

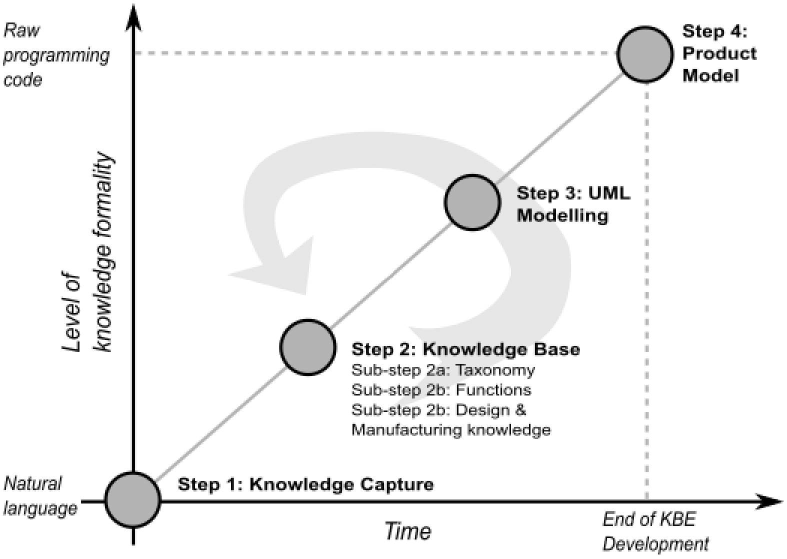

Figure 17: Knowledge formalisation process of the proposed methodology, from natural language to raw programming code

3.3.2 Step 1: Knowledge capture

The aim of this step is to elicit and collect 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 collect, due to lack of analyses / experts, and, at the same time, it is not relevant for the final delivery of the product, no implementation is needed. For those aspects that are required but not available, 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 to maximise his/her contribution. Semi-structured interviews can be then conducted to retrieve knowledge more systematically, once the problem has been set and the business case for developing the application has been defined.

Document-based research of documents already produced by the company 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). The availability of such documents varies from one company to another. A standard methodology for capturing knowledge is illustrated by Milton [85] and an example of aerospace application for fibre metal laminate (FML) panels has been developed by Emberey et al [66].

3.3.3 Step 2: Knowledge base (KB)

The next step structures the knowledge collected in step 1 by selectively sorting, storing and linking it into a knowledge base, a structured repository where knowledge is easily accessible. The creation process of a knowledge base consists of the analysis and categorization of the knowledge related to the design and manufacture of the product under question.

The process of creating the knowledge base requires the identification of the fundamental units representing knowledge (knowledge units). ICARE forms [21], standard tables representing a type of unit of knowledge, can be used for this purpose. Table 9 shows the type of knowledge these forms can represent.

Table 9: 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: “Entity-Structure”
	Function: “Entity-Function”
	Change in state of a product: “Entity-Behaviour”

Knowledge is thus represented in tables and stored into these standard forms, which are then cross-referenced (e.g.: through hyperlinks, if forms are developed in HTML), thus resulting in a network of inter-linked knowledge units. An example is shown in Figure 18 where an Entity form is referenced to a “rule” form. Graphical representations of the network help visualise 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.

Step 2 also includes the analysis of the product architecture, as explained in section 3.2. Product architecture can in fact be stored and represented through ICARE forms. The following sub-steps[4] within step 2) can be identified (Figure 19).

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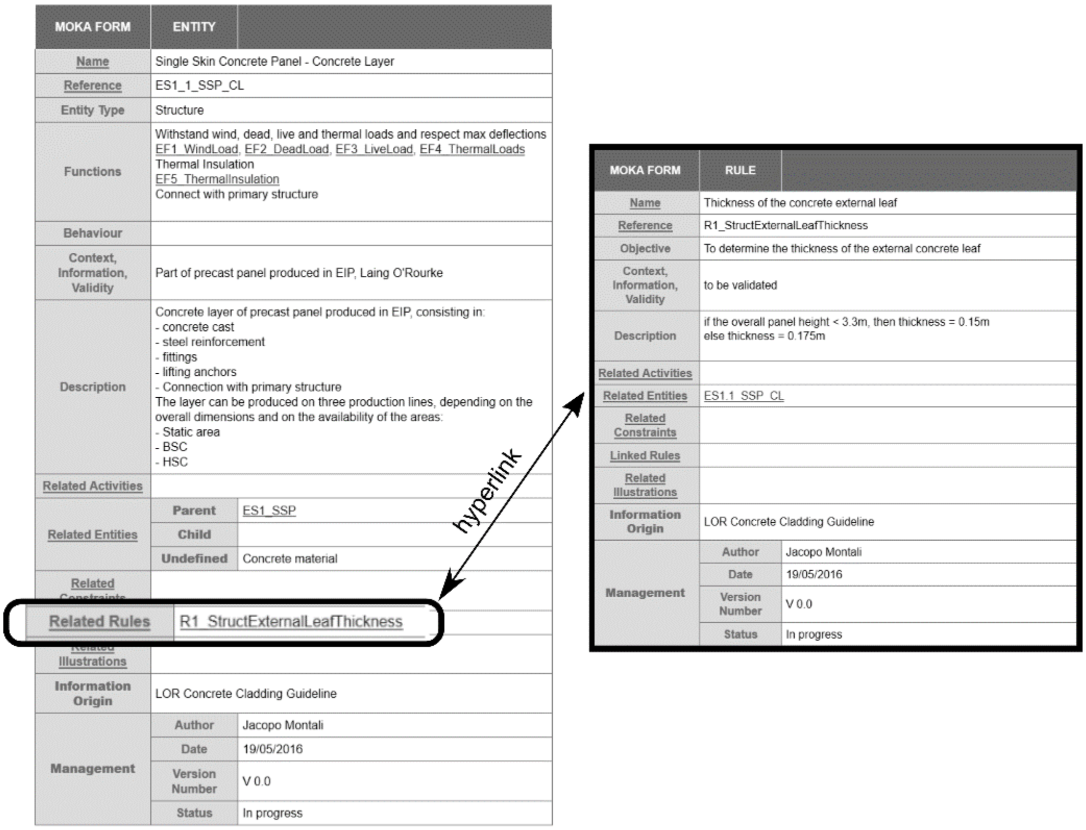
[4] Steps a) and b) correspond to steps 4) and 3) in Klein [84], respectively. The functions are selected from the “function tree” and linked to the product’s taxonomy. The taxonomy is built in turn from the “product levels”. Step c) extends Klein’s work.



MOKA FORM	ENTITY	
Name	Single Skin Concrete Panel - Concrete Layer	
Reference	ES1_1_SSP_CL	
Entity Type	Structure	
Functions	Withstand wind, dead, live and thermal loads and respect max deflections EF1_WindLoad, EF2_DeadLoad, EF3_LiveLoad, EF4_ThermalLoads Thermal Insulation EF5_ThermalInsulation Connect with primary structure	
Behaviour		
Context, Information, Validity	Part of precast panel produced in EIP, Laing O'Rourke	
Description	Concrete layer of precast panel produced in EIP, consisting in: - concrete cast - steel reinforcement - fittings - lifting anchors - Connection with primary structure The layer can be produced on three production lines, depending on the overall dimensions and on the availability of the areas: - Static area - BSC - HSC	
Related Activities		
Related Entities	Parent	ES1_SSP
	Child	
	Undefined	Concrete material
Related Constraints		
Related Rules	R1_StructExternalLeafThickness	
Related Illustrations		
Information Origin	LOR Concrete Cladding Guideline	
Management	Author	Jacopo Montali
	Date	19/05/2016
	Version Number	V 0.0
	Status	In progress

MOKA FORM	RULE	
Name	Thickness of the concrete external leaf	
Reference	R1_StructExternalLeafThickness	
Objective	To determine the thickness of the external concrete leaf	
Context, Information, Validity	to be validated	
Description	if the overall panel height < 3.3m, then thickness = 0.15m else thickness = 0.175m	
Related Activities		
Related Entities	ES1.1_SSP_CL	
Related Constraints		
Linked Rules		
Related Illustrations		
Information Origin	LOR Concrete Cladding Guideline	
Management	Author	Jacopo Montali
	Date	19/05/2016
	Version Number	V 0.0
	Status	In progress

Figure 18: 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

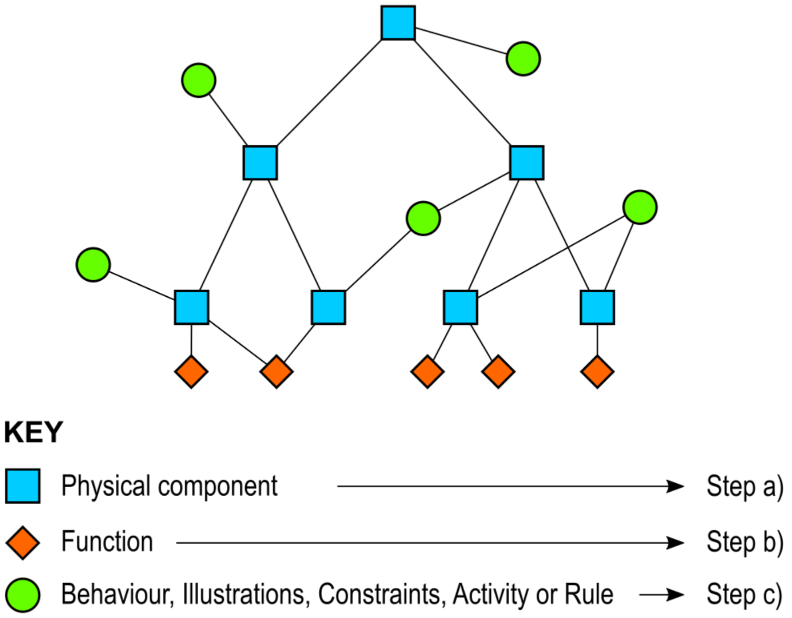


Figure 19: Graphical representation of the three sub-steps to build the knowledge base in step 2

Sub-step 2a: define the product taxonomy

This step involves the analysis of the product's physical components and their part-whole relationship, thus leading to the definition of the product taxonomy (or "product breakdown"). For example, if we consider the "unitised façade system" as the overarching product, its subcomponents will be the structural mullions, the infill panels (glazed or opaque), the connections with the primary structure and the gaskets. The components are represented by blue squares (Figure 19), and the continuous line that connects them represents the part-whole relationship (aka "contains" relationship). The component positioned above a generic component represents the "whole", whereas elements located below it represent its "parts".

The relevant MOKA forms ("Entity-Structure" form) representing the physical entities are then created based on the taxonomy and stored in the KB. The part-whole relationship is expressed through links (e.g.: hypertext) placed in the appropriate field of the MOKA "Entity-Structure" form.

Sub-step 2b: associate the product's functions to the taxonomy

The creation of the product taxonomy is then followed by the connection between the functions and each physical component. Once the functions of the product have been specified, they are associated with the corresponding physical components. Following the example in Figure 18, the "connect to primary structure" function will be linked to the connection between the panel and the structural slab, whereas both the "provide thermal insulation" and "withstand wind loads" functions will be associated with the structural mullions and the infill panels, respectively. Figure 19 shows the functions as orange rhombuses, and the connections to the physical components (blue squares) represent the link between the physical components and their functions.

The functions are stored in the KB by creating "entity-function" forms and by linking each function to a specific physical entity from the previously-created "entity-structure" forms.

Sub-step 2c: associate design knowledge to the taxonomy

In this step the design & manufacturing knowledge collected in step 1 of the methodology (knowledge collection) is associated with a specific physical element. In the above example of the unitised system, a "maximum glazed element dimensions" constraint that defines the maximum width and height of a specific glass infill panel will be associated with the manufacturing constraints of glazing units. In Figure 19 these elements are represented by green circles and they are linked to physical components (blue squares). The link represents the association between a design criterion (rule, constraint) and the corresponding physical component.

The design & manufacturing rules/constraints are included in the KB by creating the MOKA forms for Rules, Constraints, Activities and Illustrations for each unit of knowledge collected and by linking the forms to the relevant "Entity-Structure" forms representing the physical components. The MOKA form can include the original knowledge source, if necessary (e.g.: contact person, document reference, etc..).

3.3.4 Step 3: UML Modelling

The next step after knowledge collection and its structuring in the KB is the implementation into a more formal (i.e. lower level) language. Unified modelling language (UML) [86] is used to model each knowledge unit through an object-oriented approach, where each physical product component and function (i.e. "entity" ICARE forms) are represented by a class. Through OOP, it is also possible to model the engineering rules ("rule" ICARE forms) and constraints ("constraint" ICARE form) by specifying the function.

UML captures all the features characterising OOP in terms of interrelationship between classes, such as inheritance, association, composition and aggregation. The taxonomy of the product is therefore created: Figure 20 shows a typical "composition" link between the product and its subcomponents, represented by a black diamond, describing the "contains" relationship between physical entities. Once the taxonomy has been defined, the design and manufacturing knowledge is included into the taxonomy to form a lower-level ontological framework of the product.

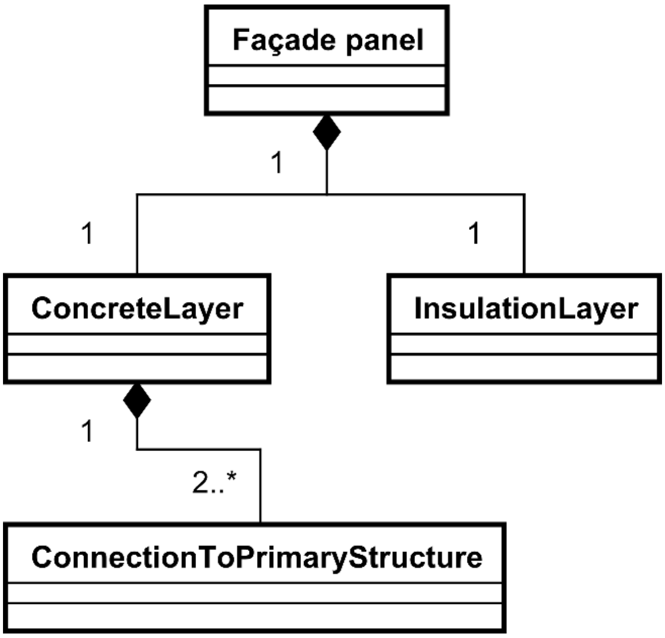


Figure 20: Simplified UML diagram showing the taxonomy of a façade product. Each box corresponds to an "Entity" MOKA form

3.3.5 Step 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, where new knowledge is included or replaces outdated concepts. The development of a software architecture that facilitates 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 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). An implementation of the PM is shown in chapter 4.

3.4 Use-case scenarios

Once the digital tool is developed, its use should be integrated into the current design process. The use of the digital tool is analysed in this section from the point of view of a façade manufacturer in particular when design development could be supported during early design stages. Consortia of companies could also be formed to reduce development costs while integrating multiple manufacturing criteria / product data in a single platform. Three possible use-cases are shown, based on two different British procurement methods [15], in which the manufacturer may or may not be appointed for developing the design at early stages. Online process maps in a BPMN notation [28] of the use-cases have been developed [87] by the author for the purposes of this study and are shown in Figure 21Figure 22Figure 23.

3.4.1 Case 1: Digital 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, the tool has been developed by a specific manufacturer (lower "swimlane") and made available to download (e.g.: on their website). A design team downloads the tool and develops the design solution (upper "swimlane"). The goals of the users of the application are both to evaluate the level of early "tenderability" (defined as the ease in delivering a project as planned and in line with the bidder's capabilities) by that specific manufacturer, including preferred materials from the supply chain and understand if the design meets some specific design intent. If the architectural intent is met, then they can move to the next design stages, otherwise they can contact the manufacturer and place a specific enquiry (e.g. about more bespoke solutions not included in the digital tool) to the technical team within the manufacturer's company.

3.4.2 Case 2: 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 commercial confidentiality. The manufacturer therefore provides a service to the design team by using the tool internally for rapid and quick support activities (Figure 22). If the architectural intent is met, then the manufacturer can send the results to the design team, otherwise more human resources are needed and more support is dedicated to the design team.

3.4.3 Case 3: Tool used by the project team across design stages in a design-build (DB) environment

In this case, the tool is developed for the design team a-priori. The tool thus becomes central to the design team, whose activity is to develop solutions within the space defined by the tool. If the 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 agile software development should be considered.

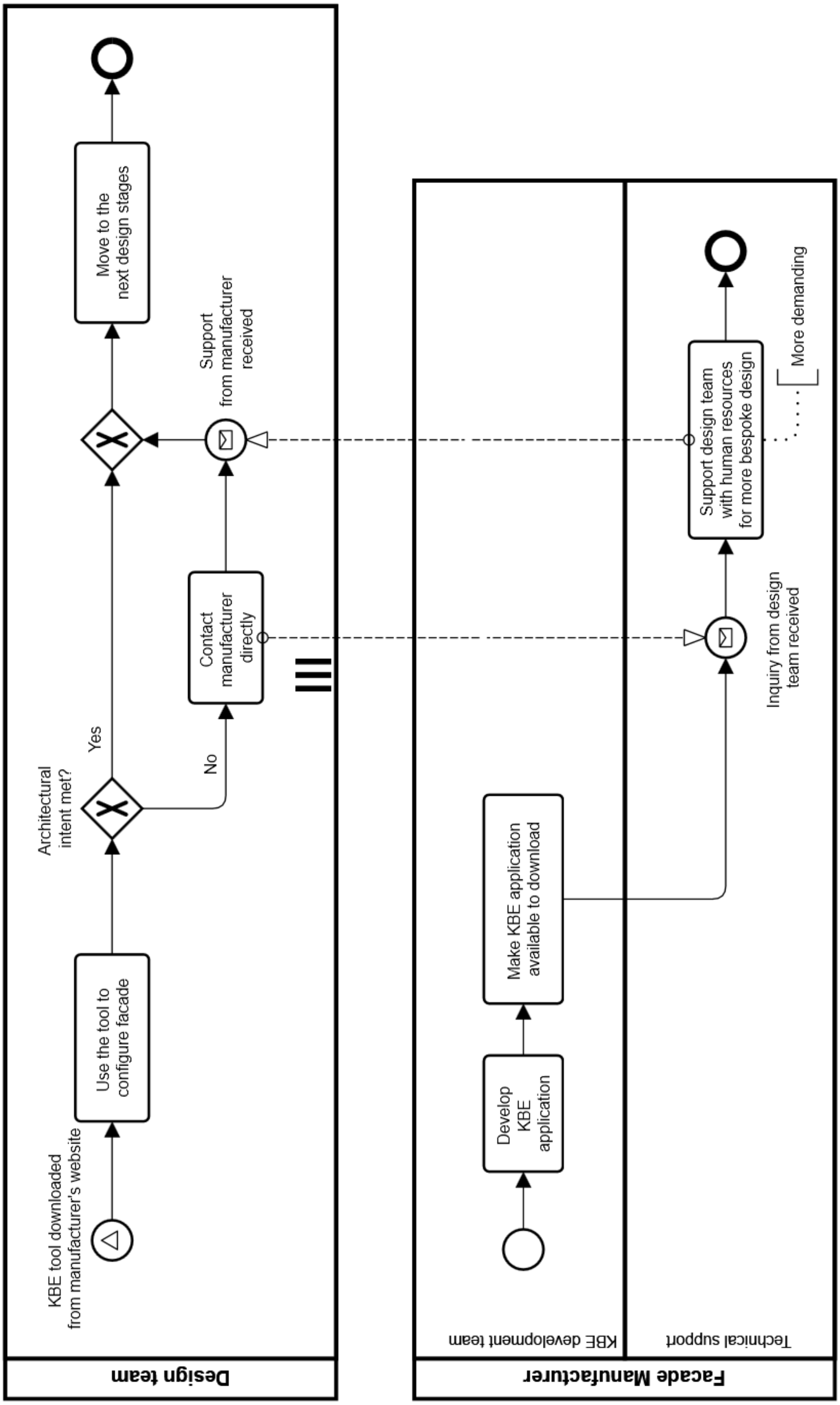


Figure 21: BPMN process map for case 1

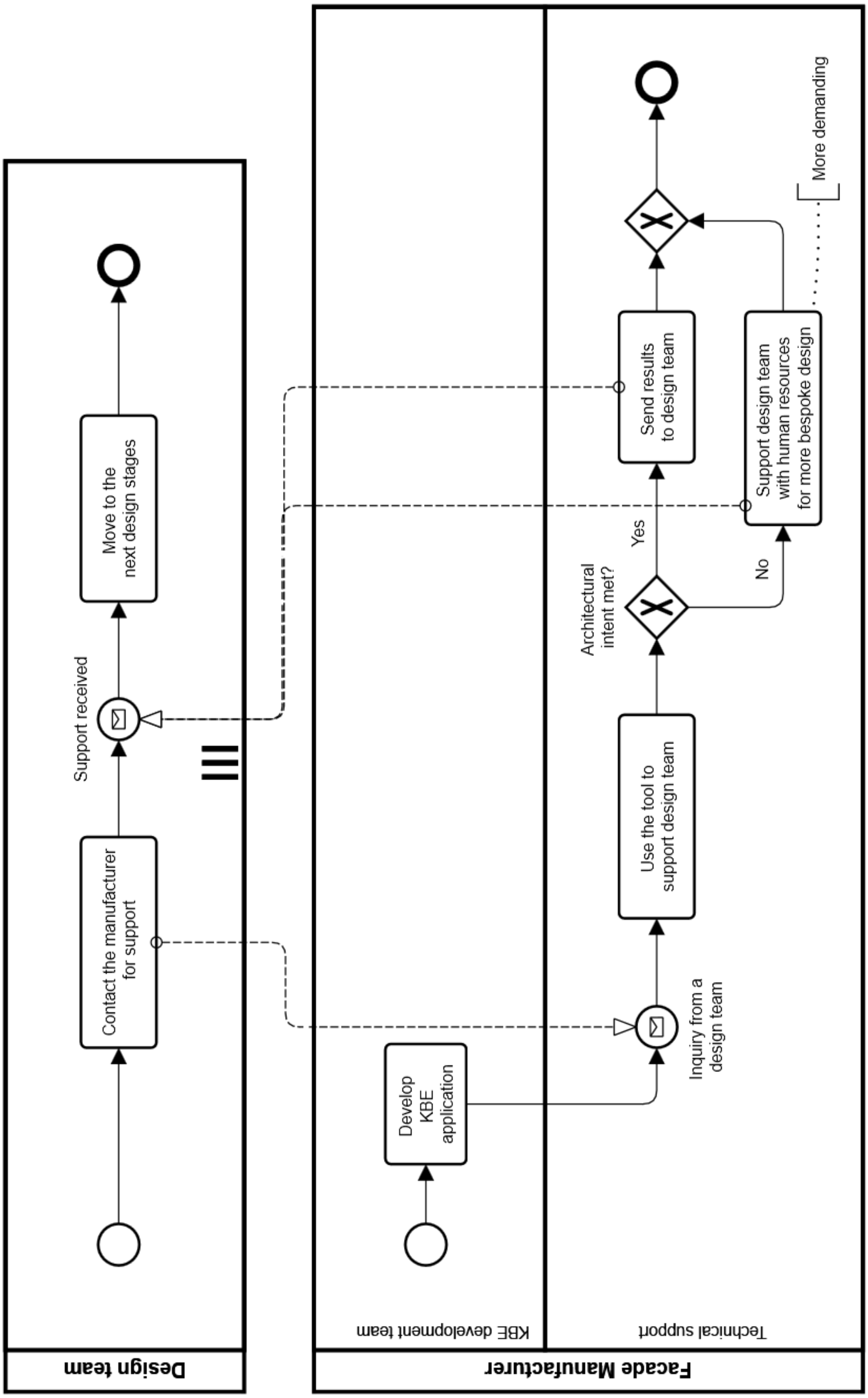


Figure 22: BPMN process map for case 2

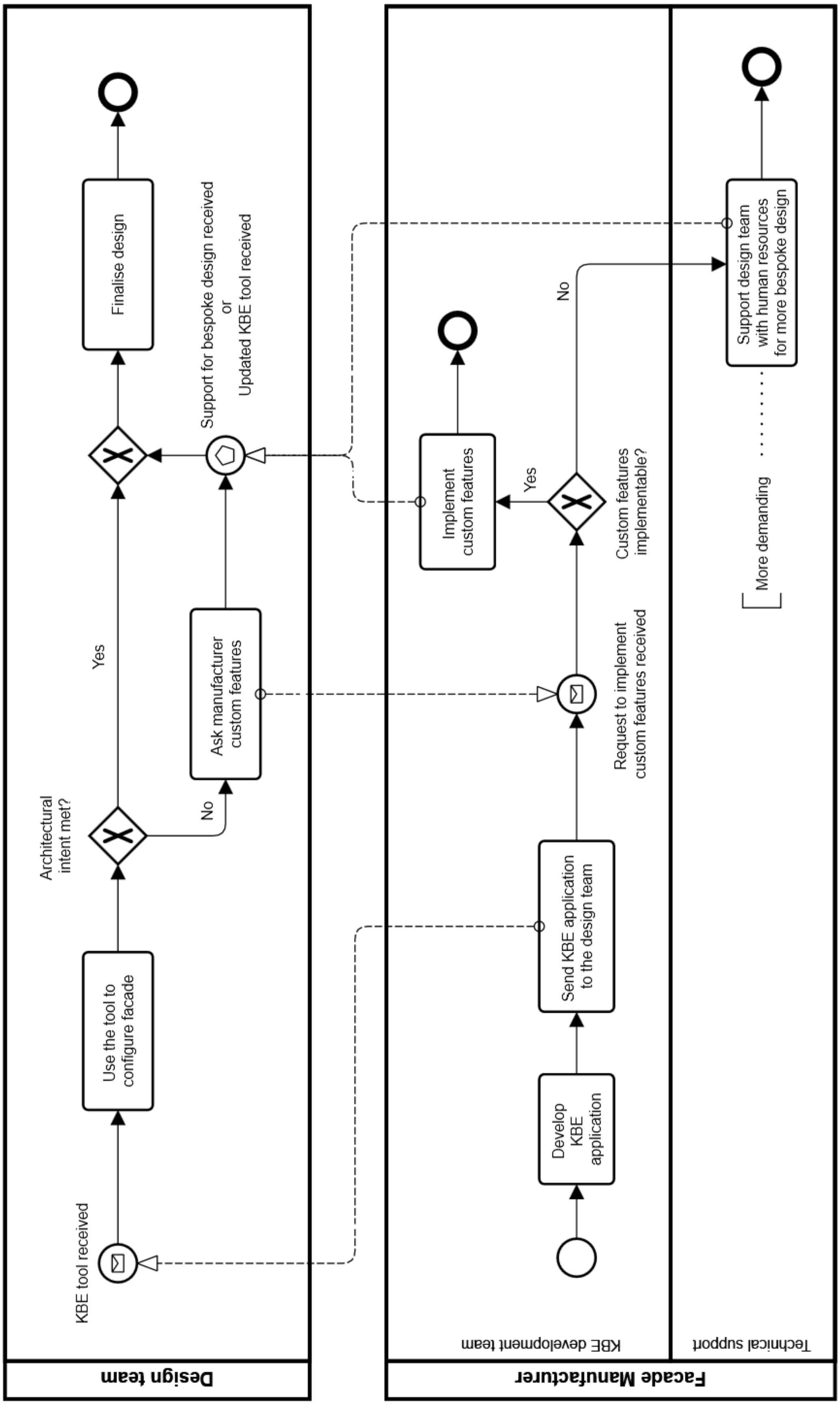


Figure 23: BPMN process map for case 3

3.5 Conclusions

Chapter 3 describes the development of a methodology that underpins future digital tools for supporting façade design. It was shown that existing methodologies, such as KNOMAD, have limited application in façades due to lack of study of the façade's product architecture and the large effort that can lead façade professional not to implement them. Therefore, in order to answer SRQ2 in section 1 it was necessary to introduce the background to the concepts of product architecture, OOP and how they are interrelated. Then, a 4-step methodology that incorporates these two concepts was developed. The methodology proposes a smooth transition of the design & manufacturing knowledge from the initial natural, unstructured form into a more rigorous and hard-coded format, resulting in a digital KBE tool. The chapter concludes with three BPMN process maps for real-world applications.

This chapter provides simplified use case scenarios to illustrate the methodology, but stops short of implementing them on a fully-fledged real-world case study. This will be performed in chapter 4.

Chapter 4

A digital tool for the design of precast concrete panels

4.1 Introduction

A 4-step methodology for implementing digital applications that support design of façade products was introduced in chapter 3. The methodology aims at collecting knowledge and increase the language's level of formality until the final implementation into the product model. In the present chapter, the methodology is implemented for a specific product: the precast concrete (PCC), single-leaf, "punched" panel manufactured in the Explore Industrial Park (EIP) in Steetley, UK. Section 4.2 describes the design & manufacture characteristics of the product, followed by section 4.3 that will go through the 4-step methodology. The chapter concludes with comments about the process and the answer to the research question SRQ3.

4.2 The precast concrete (PCC) single-leaf, "punched" panel

4.2.1 Design aspects

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. They also provide other non-structural performance requirements such as 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 24 - left). The external layer functions as a weathering protection and for aesthetics purposes. The structural layer, made from precast reinforced concrete, provides structural strength and stiffness. Pre-formed insulation boards, with integrated 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, to meet the unique combination of design requirements. The interior layers of the panels are usually completed on-site, with a metal stud frame supporting a double plasterboard giving a smooth inner finish.

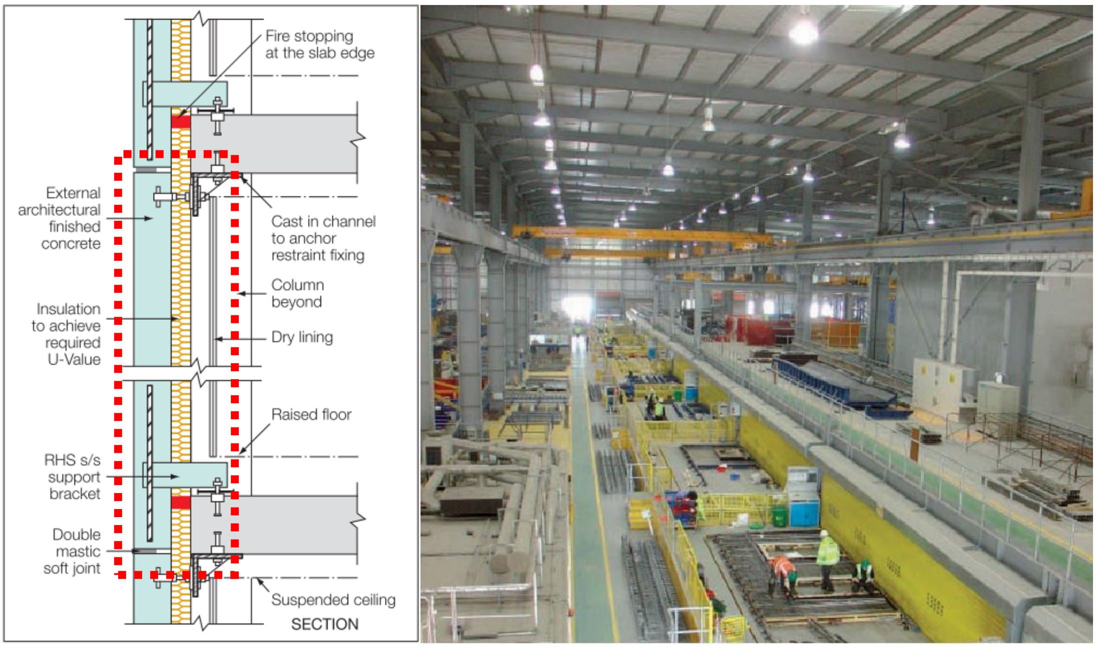


Figure 24: Vertical section of a precast single-skin concrete panel (left) and the “bespoke carousel” production line for concrete façade panels at the Laing O’Rourke’s Explore Industrial Park (EIP), Steetley, UK (right). Photo by courtesy of Laing O’Rourke plc.

Single-leaf panels are commonly referred to as “non-loadbearing”, since the structural layer of the panel is designed not to bear loads from other building elements. This decouples the structural design of such panels from the rest of the structure (but not vice versa), thereby allowing local design models to be used. The panels are often referred to as "punched" in that the openings (windows and external doors) are installed offsite (i.e. at the precast manufacturing facility) to reduce the amount of onsite operations thereby increasing delivery efficiency.

Single-leaf panels require structural connections with the primary structure, which are usually provided by steel beams or plates. The structural design of the connections depends on the geometry and the relative position of the primary structure to the PPC: in this case, the design of these connections 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. Other non-structural connections / interfaces, such as sealants, mastics and fire-stops control the fluxes of air, water, noise and fire-driven heat through the remaining interfaces.

4.2.2 Manufacturing aspects

The panels used for this study are produced in the Explore Industrial Park, Steetley (UK), the precast concrete manufacturing facility owned by Laing O'Rourke plc. The factory has 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 [88]. Single-leaf panels are produced in the BSC line, a semi-automated carousel (Figure 24 - right) where mobile steel pallets form the horizontal plane on which the façade panels are manufactured. Steel pallets are moved to different stations via a conveyor belt. In the stations various specific activities, such as mould set-up, steel reinforcement and fittings assembly, and concrete pouring are performed. Stations also present limits in terms of geometry and weight of the panel; the use of standard elements from the supply chain, such as insulation, concrete and connections also drives the ease, and therefore the cost, of manufacturing a specific solution. Logistical aspects, such as minimum / maximum dimensions and weights for transportation, form a series of design constraints to be considered into the panel's design. The design of such panels is unlikely to be economic and feasible unless these limitations are considered, thus shifting the design activity towards a design for manufacturing and assembly (Appendix B) approach. As knowledge of these limitations normally originates from downstream in the design process (e.g. detailed design or even construction stage), the early-inclusion of this knowledge upstream in the process is the key to devise economic design solutions.

4.3 The digital tool development

4.3.1 Step 1: Knowledge collection

The first step consisted in collecting the knowledge from relevant people within the company. Relevant people included, for instance, experts in the manufacturing division of the company giving advice on the constructability issues arising at late-stages, or people working at earlier stages on the thermal design of the panel (either directly or by supervising external consultants). All useful knowledge was then stored and used later to build the product model. A series of semi-structured interviews were initially conducted. To facilitate the process of knowledge collection, the interviewees were shown the latest version of the developed tool and asked to provide comments. Once the feedback about the tool was collected, the discussion moved towards adding more design and manufacturing rules/constraints to the model.

4.3.2 Step 2: Knowledge base

Step 2 is divided into three substeps: 2a to create the product's taxonomy, 2b to associate the product functions and 2c to associate all design and manufacturing criteria.

Sub-step 2a: product taxonomy

Sub-step 2a investigates the taxonomy of the product by considering the fundamental components that constitute the panel. The taxonomy is characterised by a relationship between the overall product and its constituents (in accordance with Klein's "product levels" [8]) of the type "contains". The taxonomy for the precast, single leaf panel is shown in Figure 25, in which each element is associated with a corresponding “entity-structure” ICARE form that stores information about their upper- and lower- level constituents. Grey boxes in Figure 25 represent the “leaves” of the diagram, which were then assigned a function in step b). An “entity-function” form was created to store a description of the function.

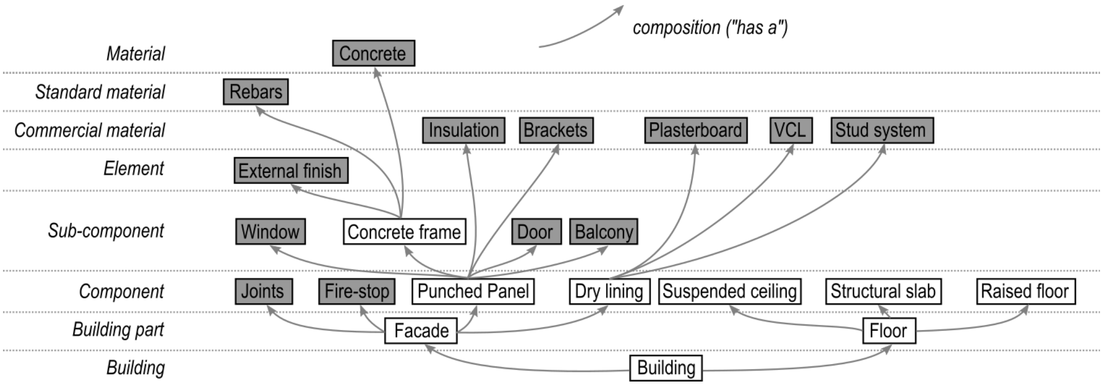


Figure 25: Taxonomy of the product model of precast concrete single-skin panel, based on the classification scheme proposed (“product levels”) by Klein [8]. *Grey boxes represent the “leaves” of the tree*

Each component was then stored in a corresponding MOKA “Entity-structure” form. The “parent entity” or “child entity” fields of the form were filled with hyperlinks to the corresponding references to the “Entity-structure” forms representing the “whole” and the “part”, respectively[5].

Sub-step 2b: product functions

The second part of step 2 consists of linking the product’s functions with the physical components defined in the previous sub-step. This is represented diagrammatically in the directional force-directed layout shown in Figure 26. The meaning of the directed arrow depends on the start and end elements: if an arrow points to an “entity-structure” element (dark green circle) from an “entity-function” element, this signifies that the link will be of the type “function associated with the physical element”. Conversely, two “entity-structure”

---

[5] Although “parent entity” and “child entity” might not be appropriate terminologies to represent the part-whole relationship, this notation has been maintained for consistency with the original MOKA forms. Future work should seek to modify such forms with façade-specific fields and fields names.

elements connected to another share a part-whole relationship ("has a"), as per sub-step 2a.

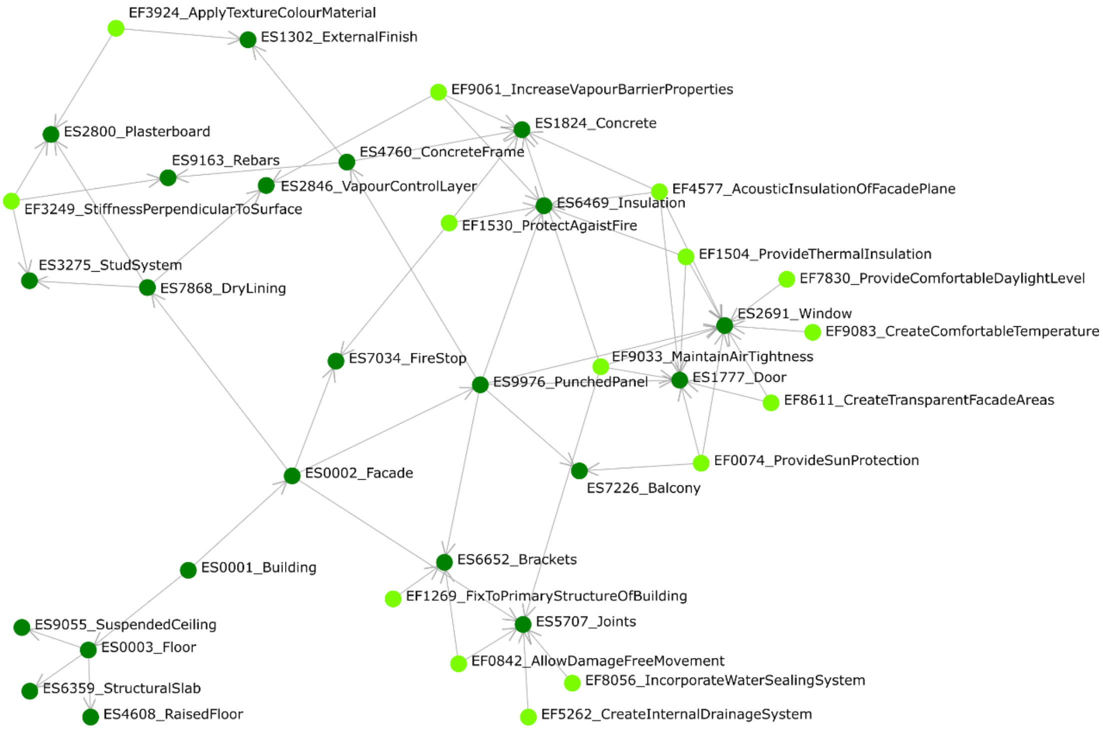


Figure 26: Taxonomy of the product model of precast concrete single-skin panel (dark green dots) and associated functions (light green dots) in a force-directed layout generated in D3.js [34]

Sub-step 2c: design and manufacturing criteria

The ontological framework of the product model hitherto created includes information about the product breakdown and the associated functions. Sub-step 2c adds knowledge about rules and constraints associated with the design and manufacture of the product, which was collected in step 1. This is achieved by creating the remaining "illustration", "rule", "constraint" and "activity" forms and by linking them with the relevant "entity-structure" and "entity-functions" forms created in the preceding steps.

For example, the rule governing the thickness of the structural concrete layer has been developed through a case-based, multi-linear regression by analysing a series of existing projects of the precast concrete manufacturer. The formula presents a lower bound given by an *if…then…* heuristic rule. The rule was defined as follows:

$$t = A \cdot H + B \cdot WWR + C \cdot NOp + D \cdot Complexity \quad (1)$$

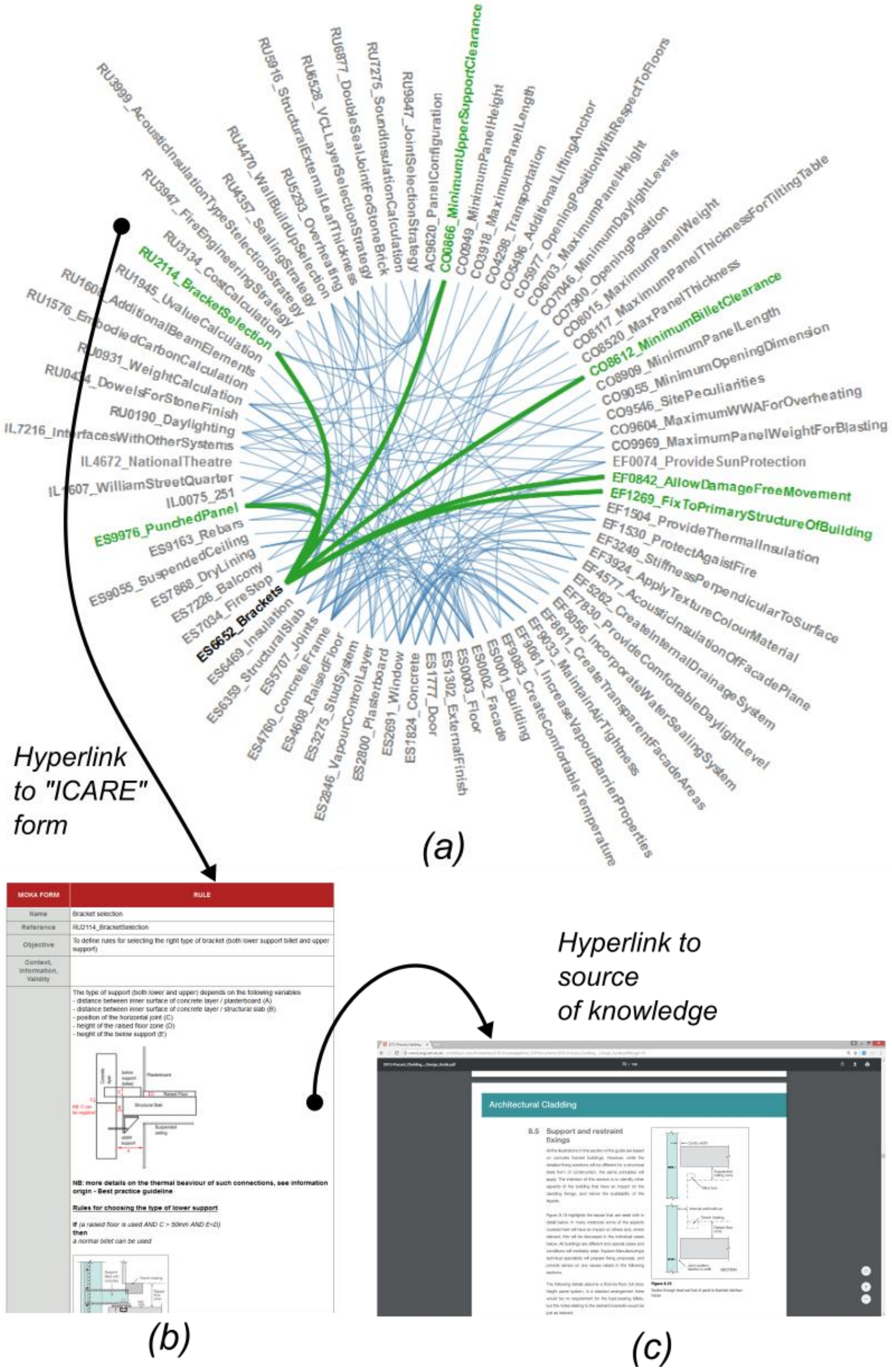
$$with t < t_{min} = if(H < 3.3m), then(0.15m), else(0.175m) \quad (2)$$

where H is the height of the panel, WWR is the window-to-wall ratio, NOp is the number of openings in the panel, $Complexity$ is equal to zero if the panel is a flat external surface and unity if it has an external faceted geometry, and A, B, C, D are constants. The rule was then stored in a corresponding “Rule” form and linked via hyperlink with the “entity-structure” form describing the concrete frame of the precast panel.

Knowledge about constraints is included into forms and it is usually applied to rules. For example, the maximum weight for lifting operation in the factory is 250kN (operated by a tandem crane) or 125kN (if operated by a single-gantry crane). This value is stored in a specific form and linked to a Rule form determining the weight of the panel.

The final product is a network of interrelated concepts, creating semantic links between features for defining product architecture, such as physical components and their functions, and design and manufacturing criteria under the form of rules and constraints. Given the large number of links between knowledge units, the final knowledge base was represented by a so-called hierarchical edge bundling, to reduce the “visual clutter when dealing with large numbers of adjacency edges” [37]. The knowledge base distinguishes between “hard” and “soft” constraints: the first is interpreted as a design error and the second as a warning, i.e. feasible, but that might have consequences on the performance or cost of the design solution. Figure 27 shows the diagram generated through the Javascript library D3.js [34].

The resulting KB works as follows. From the hierarchical edge bundling, the user can hover on specific elements such as rules, constraints, description of a physical component or its functions. The diagram is interactive in that it highlights in green all the links and interrelated elements to that specific element. By clicking on a specific element, the user is redirected by hyperlink to a webpage containing the MOKA form describing the element in question.



MOKA FORM	RULE
Name	Bracket selection
Reference	RU2114_BracketSelection
Objective	To define rules for selecting the right type of bracket (both lower support billet and upper support)
Context, Information, Validity	
	The type of support (both lower and upper) depends on the following variables - distance between inner surface of concrete layer / plasterboard (A) - distance between inner surface of concrete layer / structural slab (B) - position of the horizontal joint (C) - height of the raised floor zone (D) - height of the below support (E) **NB: more details on the thermal beaviour of such connections, see information origin - Best practice guideline** **Rules for choosing the type of lower support** **If** *(a raised floor is used AND C > 50mm AND E<D)* **then** *a normal billet can be used*

Figure 27: Knowledge base in the form of Hierarchical Edge Bundling [34,37] and links to more detailed descriptions of the underlying knowledge related to the selection of the supporting brackets for precast concrete single leaf panel: a) overarching view of the links with other elements of knowledge, b) MOKA "Rule" form containing the logic and c) original source of knowledge

The form contains further links to the sources of knowledge. In the example shown in Figure 27, the user hovers on the rule “RU2114_BracketSelection”. By clicking on the hyperlink, a webpage is opened containing the logic behind the selection of the appropriate support bracket for the precast panel. The form also contains a field (“information origin”) with a hyperlink to a specific page of a PDF document containing the original source of knowledge. In this way, it is possible to achieve different levels of granularity of the relevant information/knowledge, from the highest level possible (the hierarchical edge bundle), to the most detailed description (the original PDF document).

4.3.3 Step 3: Unified Modelling Language (UML) class diagramming

The definition of the fundamental components of knowledge and their storage into appropriate forms is followed by a UML class diagram to represent the product architecture. Figure 28 shows the generated diagram, in which each class represents a physical component. Functions (e.g. thermal) and properties (e.g. weight) are assigned via interfaces that are implemented by the classes. In some cases, interfaces were not assigned to certain elements since they have a negligible effect on the performance of the panel (e.g. vapour control layer on total weight).

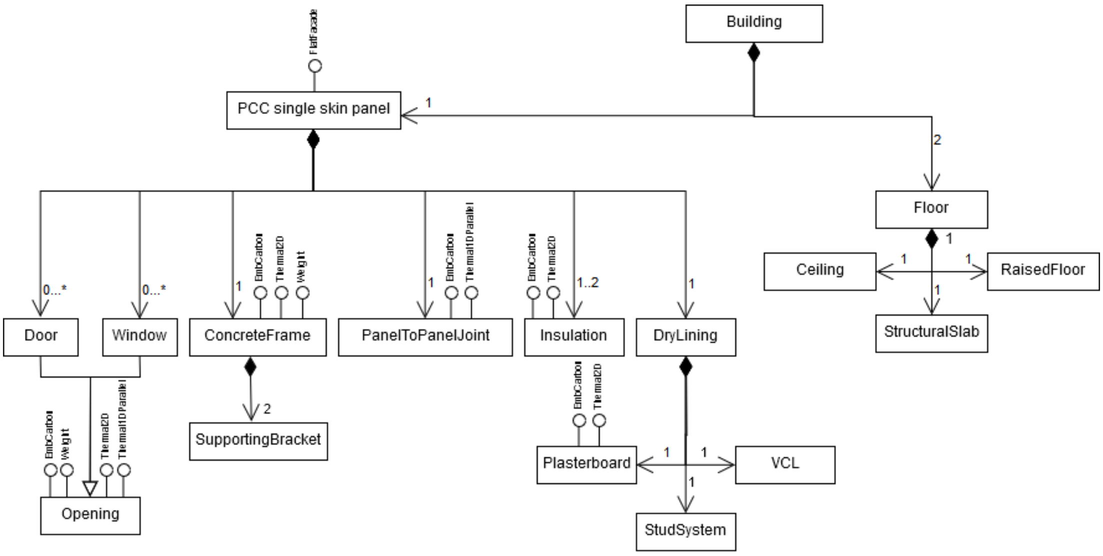


Figure 28: UML diagram representation of the product architecture

For example, the “PanelToPanelJoint” class function implements the “IThermal1DParallel” interface since joints are one-dimensional elements, parallel to the surface of the façade, that dissipate energy through the linear thermal transmittance along the length of the joint. Thus, the interface requires all elements that implement the class to include the two properties “psi” (linear thermal transmittance, W/mK) and “length” (length of the joint, m).

```
public interface IThermal1DParallel
{
        double psi { get; set; }
        double length { get; set; }
}
```

4.3.4 Step 4: Digital tool implementation

The last step consists of the implementation of the PM into a usable digital tool. The chosen platform was Rhinoceros 5 by McNeel Associates and the tool was under the form of a series of Grasshopper’s custom components written in C# representing the product model (Figure 29). The user starts by drawing the surface representing the overall façade and by assigning a specific Grasshopper definition to the surface. Then, by double-clicking on a specific custom component, a Graphical User Interface (GUI) allows the user to (Figure 29):

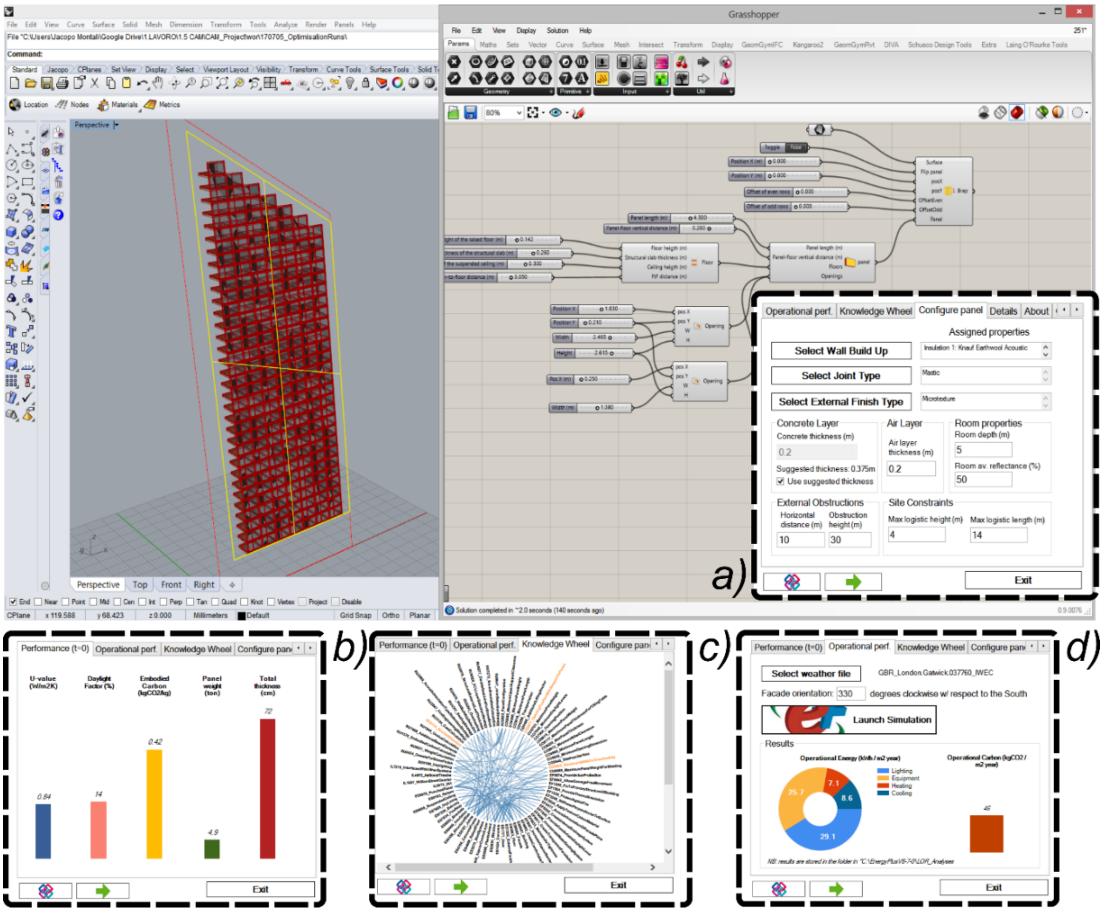
a) Configure the panel in terms of build-up, the type of jointing solutions, the external finish type, as well as other properties such as the thickness of the concrete layer (which can be automatically determined based on the rule described in sub-step 2c) or the thickness of the air layer. All configurations are selected from a database, which embed knowledge about the preferred design & manufacturing practices from the manufacturer (e.g. panel’s build-ups, insulation types).

b) A series of performance indices are automatically calculated based on the selected configuration, such as U-value, daylight factor, embodied carbon, panel weight and total panel thickness.

c) The KB shown in section 4.3.2 and represented by the hierarchical edge bundling automatically highlights, as the user configures the PM, if any constraint is violated. If the constraint is of the type “hard”, then the corresponding element will turn red; if the broken constraint is “soft”, then the text will turn orange. In this way, the user is instantaneously informed about the consequences of their design choices.

d) It is also possible to determine an early-stage estimate of the expected operational energy/carbon by running a dynamic, single zone energy simulation at run-time via a link to Energy Plus, based on the solution that is currently configured by the user.

A more in-depth overview of the capabilities of the tool is shown in Appendix D.



Assigned properties
Select Wall Build Up: Insulation 1: Knauf Earthwool Acoustic
Select Joint Type: Mastic
Select External Finish Type: Microtexture

Concrete Layer
Concrete thickness (m): 0.2
Suggested thickness: 0.375m
☑ Use suggested thickness

Air Layer
Air layer thickness (m): 0.2

Room properties
Room depth (m): 5
Room av. reflectance (%): 50

External Obstructions
Horizontal distance (m): 10
Obstruction height (m): 30

Site Constraints
Max logistic height (m): 4
Max logistic length (m): 14

Select weather file: GBR_London.Gatwick.037760_IWEC
Facade orientation: 330 degrees clockwise w/ respect to the South
Launch Simulation
Results
Operational Energy (kWh / m2 year)
Operational Carbon (kgCO2 / m2 year)
NB: results are stored in the folder in "C:\EnergyPlusV8-7-0\LOR_Analyses

Figure 29: Digital tool’s GUI for panel build-up configuration (a), performance analysis (b), compliance to constraints (c), and operational performance via Energy Plus (d)

4.4 Discussion

4.4.1 Tool development process and final release

The developed tool integrates design and manufacturing knowledge from various sources into one single platform. To the best of the author's knowledge, this is the first of this kind in the façade sector. The tool addresses the challenges affecting façade design and the limitations of currently-available digital tools described in chapter 1. The methodology for creating the tool (Figure 17) was iterated several times during the course of the research program; the typical iteration spanned from adjusting the GUI with additional functionalities (e.g. window tab for illustrating typical details), to including constraints or calculation of performance indices (e.g. panel weight or total thickness). A complete overview of the final version of the tool is given in Appendix D.

In total, approximately 20 iterations were required to complete the tool over the course of 12 months. This excludes the 6 months (3+3) spent at the industrial partner's premises (3 days/week) to conduct interviews and to further develop the tool. The time spent at the industrial partner's premises was essential in terms of knowledge capture and advances in tool development.

In its current form, the tool works without technical issues and the performance calculations and constraint checking are done almost instantaneously. The tool is set in such a way that the algorithm runs automatically at every change in the product model (e.g. GH slider changed, or insulation type or thickness changed) by using C#'s specific or custom-built "events". Only the Energy Plus analysis requires prompting by the user, by pressing the "Launch simulation" button (Figure 29d).

4.4.2 Challenges and limitations

There was a series of limitations/obstacles that were encountered during the application of the methodology and the tool implementation. First, it was challenging to capture the industrial partner's initial requirements and to convert those requirements into a usable tool. Although the industrial partner was aware of the overarching problem, the main difficulty was to deconstruct it into sub-problems with different levels of priority. This was mostly motivated by the fact that no prior attempt of this sort had ever been made. Also, no initial feedback was provided to the author, since an implementation of the tool was not provided to the industrial partner in the first place. In order to overcome this problem, the author developed a series of initial tentative solutions (e.g. digital tool to calculate the appropriate concrete thickness with a very basic GUI), followed by an initial feedback collection campaign. As the industrial partner became aware of the tool capabilities, further implementation requests were raised from the industrial partner and the conversation became more and more prolific. The main limitation of this approach was the time needed to start meaningful conversation between the two parties.

The second limitation consisted in the intrinsic contrast between the need to model the product under analysis to a high level of detail and the applicability of the PM to multiple projects. If the PM is in fact too detailed (e.g. modelling all geometric intricacies such as rebates and chamfers), its application will be constrained to a smaller set of projects; if the PM is instead sufficiently generic to be scalable to a wide spectrum of cases, its reusability will allow the initial development cost to be spread across multiple applications. The author chose this second option, which has also had the benefit of yielding a simpler and more maintainable code. Nevertheless, it is undeniable that modelling few geometrical detail leads to a lower graphical impact for the user. The correct balance between real-world detail and digital implementation effort should therefore be achieved by using abstraction (see section 3.2.2). This balance should be evaluated on a product-by-product basis. Concrete panels are subjected to more topological variations than standard façades such as aluminium-framed curtain wall systems: the former should therefore be abstracted by simplifying its features, whereas the second could be modelled to higher detail (e.g. Shueco parametric system [74]). As a general rule, the greater the topological variations in a façade, the more abstraction is needed.

4.5 Conclusions

The present chapter has shown a practical application of the methodology shown in chapter 3 to a case study of a manufacturer-specific product and related design & manufacture knowledge. The creation of the digital tool has shown that it is possible to collect and implement design & manufacture knowledge into one single digital application. The proof-of-concept was therefore demonstrated, thus answering the SRQ3. Challenges and limitations in the application and in the tool implementation were highlighted. The next chapter will show two real-world validation campaigns for the above-mentioned tool, with the aim of increasing the technology readiness level of the proposed approach.

Chapter 5

Validation of the digital tool

5.1 Introduction

The present chapter introduces the validation campaign of the digital tool developed in chapter 4. This chapter will answer SRQ4 by exploring the readiness of the digital application beyond the proof-of-concept. Two forms of validation are adopted. First, a validation test in a relevant environment is conducted by running a “hands-on” workshop at 5 London-based façade consultancy practices. This also serves to create indices that measure the effectiveness of such tools when in the hands of prospective users. Then, the tool capability are demonstrated in a real-world scenario by applying it to two real-world projects, in which the general contractor is supporting architectural design at early-design stages (e.g. via pre-construction service agreement - PCSA). The chapter concludes with final remarks and comments on the real-world trials.

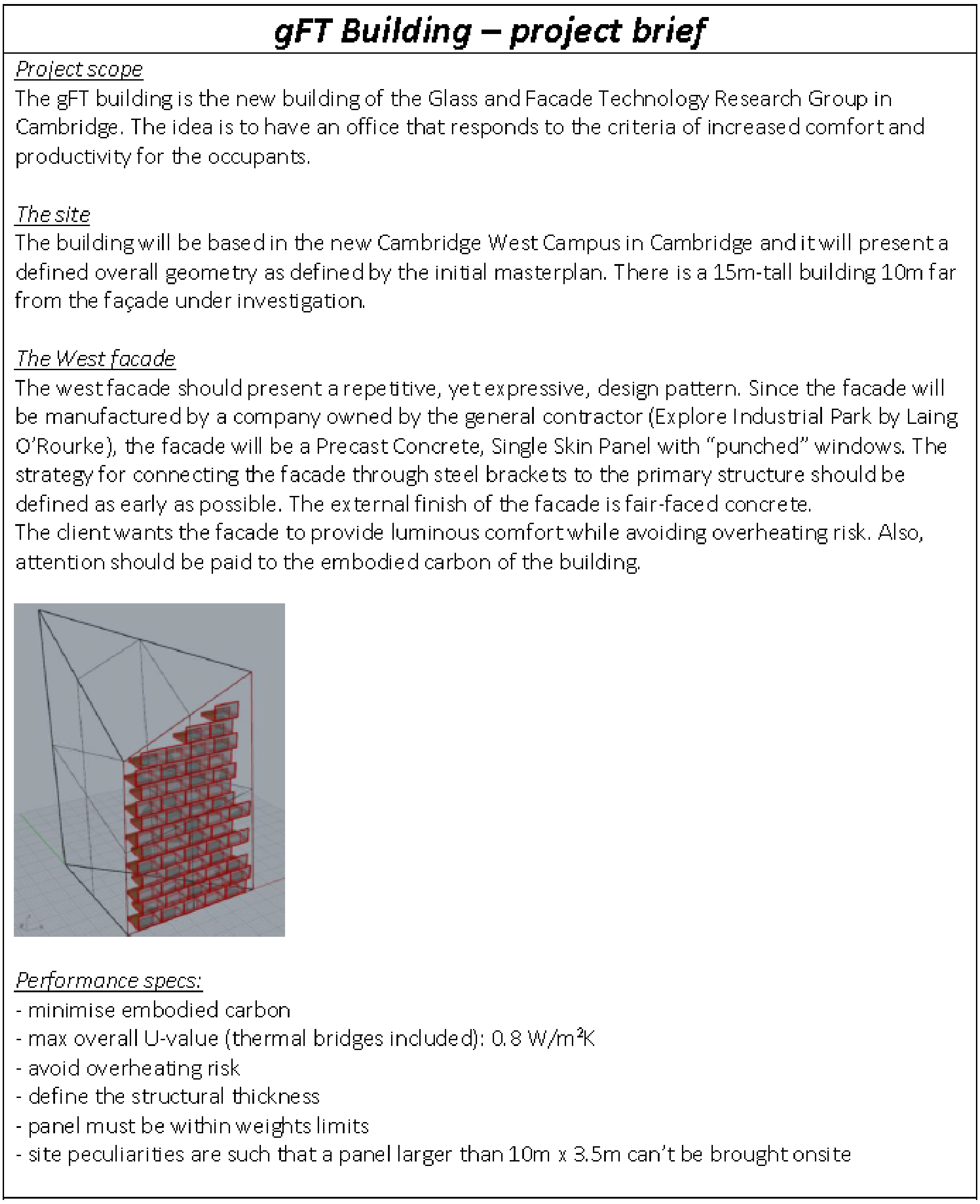
5.2 Validation 1: Tool validation at five façade consultancies

5.2.1 Introduction

There is a lack of available literature about the effectiveness of digital tools in the design process. It is also not fully understood what potential users in the AEC sector, i.e. designers, engineers and consultants, think about their adoption and how their daily work routine would potentially change. Academic studies from other industries have generally reported potential savings arising from the use of knowledge-based tools: Van Der Laan and Van Tooren [48] achieved 80% of savings in time to design the structure of aircraft movables; Kulon et al. [49] reduced the time for designing the manufacturing process of hot forging from weeks to hours; Chapman and Pinfold [50] developed a tool for building the FEM mesh of a car body-in-white in few minutes, a task that is normally performed at post-design stages as it is very time-consuming. However, no clear explanation or breakdown of costs / benefits was reported in these studies. This is one of the major obstacles in adopting those technologies in the construction industry, which generally requires clear cost / benefit justification before adopting innovative technologies and approaches.

5.2.2 The workshop

Five UK-based façade consultancies were contacted to test the digital tool. The companies involved are leaders in the AEC sector, normally working on multi-million projects across the world. The companies are either specialists working only in the façade sector or across multiple fields of civil engineering, in which case the division specialised in façades was involved. A one-hour meeting was fixed at their premises and an outline with the requirements for the workshop was sent in advance (Appendix E). Participants were required to solve a façade-related design problem in which a challenging concept design was provided (Figure 30). The problem was introduced in the context of a fictitious project through a simplified brief that described the architectural intent and the expected façade specifications. The workshop was structured as follows: 30 minutes for introduction and instructions, 20 minutes of “hands-on” session with the tool, and 10 minutes for filling out a questionnaire.



gFT Building – project brief

Project scope

The gFT building is the new building of the Glass and Facade Technology Research Group in Cambridge. The idea is to have an office that responds to the criteria of increased comfort and productivity for the occupants.

The site

The building will be based in the new Cambridge West Campus in Cambridge and it will present a defined overall geometry as defined by the initial masterplan. There is a 15m-tall building 10m far from the façade under investigation.

The West facade

The west facade should present a repetitive, yet expressive, design pattern. Since the facade will be manufactured by a company owned by the general contractor (Explore Industrial Park by Laing O'Rourke), the facade will be a Precast Concrete, Single Skin Panel with "punched" windows. The strategy for connecting the facade through steel brackets to the primary structure should be defined as early as possible. The external finish of the facade is fair-faced concrete.
The client wants the facade to provide luminous comfort while avoiding overheating risk. Also, attention should be paid to the embodied carbon of the building.

Performance specs:

- minimise embodied carbon
- max overall U-value (thermal bridges included): 0.8 W/m²K
- avoid overheating risk
- define the structural thickness
- panel must be within weights limits
- site peculiarities are such that a panel larger than 10m x 3.5m can't be brought onsite

Figure 30: design problem to be solved by consultants during the "hands-on" session

Overall, 39 people attended the 5 workshops, of which 32 performed the practical exercise. The average years of experience per each company ranged from 3 to 7 years (Figure 31). After a 20-minutes introduction, participants were instructed for 10 minutes on the use of the digital tool, which they had installed on their laptops. In some instances, participants were provided with some ready-to-use laptops brought by the author. Once the tool was set up and participants ready, the 20-min “hands-on” session began. Participants were asked to read the brief and to solve the problem by manipulating the product model of the façade. Working in small groups was also allowed. Each small group or individual working on a single machine was then given a reference number. The results of the exercise were then saved on a custom JSON file that was named with the reference number of the group / individual.

Participants were also asked to fill in an individual questionnaire (Appendix E) in the last ten minutes of the workshop. The total number of questions was 11, including general questions, attitude towards innovation in the façade sector and opinions about the exercise and the potential use of the tool in real-world scenarios. The questionnaire was also annotated with the reference number from the practical session, so that the results from the questionnaire could be matched with the corresponding results from the exercise.

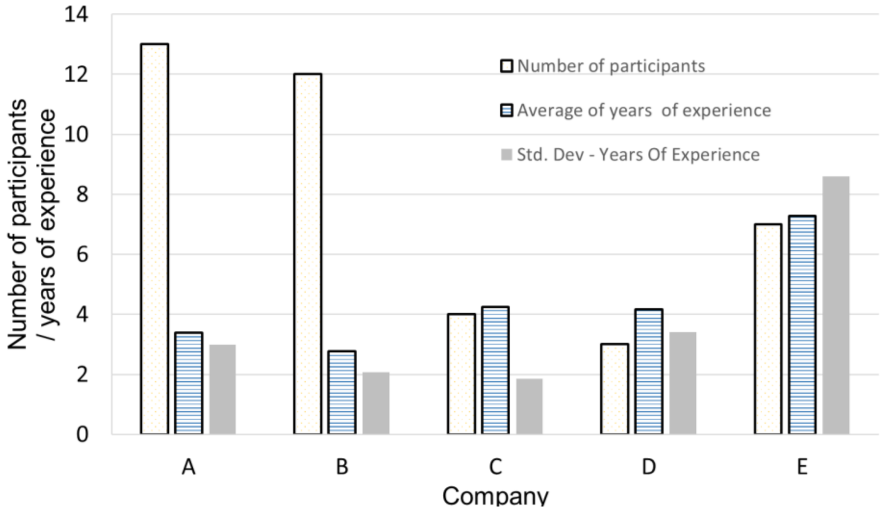


Figure 31: Number of participants, average years of experience and standard deviation per each company

The outcome of the practical exercise with the digital tool was summarised by giving scores to 4 different aspects: configuration, performance, constraints and design change (Table 10). All scores were calculated with respect to a baseline case, which was generated by the author and that was deemed to be sufficiently suitable for the given case study. The “Configuration” score assesses how easily the user could identify the correct values of the configurable features of the panel in the digital tool’s GUI, such as selection of structural bracket, wall build-up and panel-to-panel joint. The "Performance" score determined how close the configured solution was to the baseline case in terms of performance; the user, by modifying both continuous (e.g. panel's and window's dimensions) and discrete (e.g. insulation type) variables, was able to instantaneously retrieve the values of embodied carbon, U-value and daylight, as prescribed in the exercise's specification. The "Constraint" score considered how many manufacturing- (e.g. maximum panel weight) and performance-related (e.g. glare risk) constraints were violated while trying to optimise the performance by the users' configured solution.

Table 10: Criteria for evaluating the attitude to solve the exercise with the digital tool

Score name	**Description**	**Task involved**	**Score measurement***
Configuration	Ability to configure the product model	▪ select correct structural bracket (C_1) ▪ select correct wall build-up (C_2) ▪ select correct panel-to-panel joint (C_3)	Score = $\sum_i C_i$ Where C_i: ▪ 1 if correct item selected ▪ 0 if wrong item selected
Performance	Understanding façade performances and their trade-offs	▪ minimise embodied carbon (P_1) ▪ minimise U-value (P_2) ▪ maximise daylight (P_3)	Score = $\sum_i P_i$ Where P_i: ▪ min($P_{i,baseline}/P_i$, $P_i/P_{i,baseline}$) if $0.75\ P_{i,baseline} < P_i < 1.25\ P_{i,baseline}$ ▪ 0 otherwise
Constraints	Understanding the violation of manufacturing- and performance-related constraints and warnings	▪ limit the number of constraints (C) and warnings (W)	Score = $1 / C + 1 / W$ With the exception of: ▪ $1 / C = 1$ if no constraint is broken ▪ $1 / W = 0.5$ if no warning is raised
Design change	Change from original design in terms of panel's frontal dimensions	▪ select correct window type (DC_1) ▪ maintain window i-th dimensions or position (DC_{2i}) close to the original design	Score = $DC_1 + DC_2$ where ▪ $DC_1 = 1$ if window type correct, 0 otherwise ▪ $DC_2 = \sum_i A_i$ ▪$A_i = min\left(\frac{DC_{2i}}{DC_{2i,baseline}}, \frac{DC_{2i,baseline}}{DC_{2i}}\right)$ If $0.75\ DC_{2i,baseline} < DC_{2i} < 1.25\ DC_{2i,baseline}$, $A_i = 0$ otherwise
Total score	▪ general value	▪ all above aspects	▪ Sum of all scores

*All scores have been calculated with respect to a baseline case.

Finally, a “Design change” score the extent by which assesses the performance- and constraint-related adjustments made by the user deviated from the stated architectural intent, such as window type and geometrical features. Each aspect was given equal weighting and each score was measured by a dedicated dimensionless index, which was then summed to form a total score. Participants were not directly informed about the four scores at the end of the exercise.

5.2.3 Results

Results from the exercise

Figure 32 shows the results obtained from the exercise in terms of the four criteria illustrated in Table 10. Results were plotted as a function of the average experience of the groups formed by the participants (if working in couples) as shown in Table 11.

Table 11: Classes of experience of the participants

Experience class	Interval
0 (low experience)	experience < 2 years
1 (average experience)	2 ≤ experience < 5 years
2 (high experience)	experience ≥ 5 years

All groups of experience performed equally in terms of ability to interact with the GUI to configure the panel (Figure 32a). Similarly, the ability to interact with the diagram shown in Figure 32c to reduce the number of broken and unsatisfied constraints did not show any variation between the investigated groups. The major differences are shown in diagrams b) and d) in Figure 32, which then resulted in the difference in the total score in diagram e). The group that achieved the highest scores was the intermediate experience group, with nearly twice as much of the other two groups as the results obtained from the “Performance” and “Design change” tasks. The low scores from the low-experience groups suggest more difficulties to perform the two above-mentioned exercises.

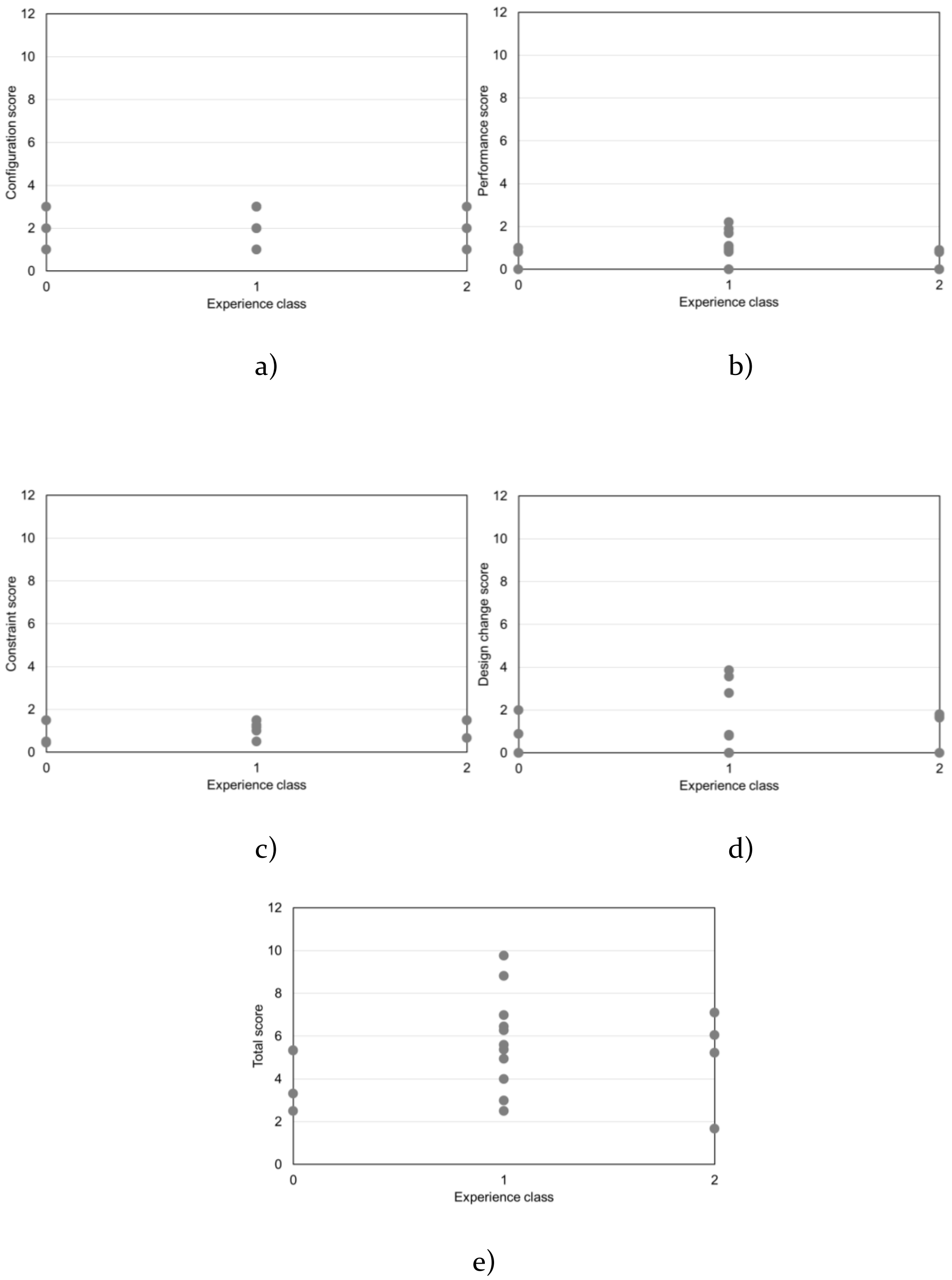


Figure 32: Results from the exercise in terms of: a) panel configuration (e.g.: build-up), b) achieved panel performance, c) manufacturing-related broken constraints, d) degree of change from the initial design and e) total score

Results from the survey

The exercise was followed by a survey that was matched with the participants' results from the exercise. Survey results are shown in Figure 33. The first two questions (a and b) identified the context and the participants' attitude towards innovation and their view in terms of challenges in the façade sector. In general, there was a large agreement that the sector lacks innovation. Apart from the lack of digital tools (rated 3.4), product complexity and bespokedness and fragmentation of the design & construction process were seen as the most relevant challenges (rated 3.10). Lack of communication / access to information had the lowest rating.

Questions c), d) and e) in Figure 33 attempted to capture the attitude of the participants towards a future use of the tool in a real environment, as well as its perceived efficacy. The intermediate experience group shows an average rating of 4.1 in terms of level of satisfaction towards the effectiveness of the tools towards the primary goal, while the other two showed ratings below 3.5. The ability to understand trade-offs between the intended design and its constraints also achieved high ratings for this group (4.1 versus 3.8). This group also found the tool less invasive in terms of architectural expression, when compared to the other two groups (3.1 versus 3.3 / 3.5).

The last two questions (f and g in Figure 33) assessed the user's perception of the pros and cons of the tool. The most valued aspect was the tool's ability to provide instantaneous feedback on the façade panel's performance when changes are made (rating 3.8). The integration of the tool into an existing platform, as well as the ability to integrate more design aspects, were rated second in importance. All participants found the tool not entirely user-friendly, which was confirmed to be the second-most important improvement needed in question g) in Figure 33. The major requirement was the presence of more detailed features, such as the visual representation of panel-to-panel joints, supporting upper and lower brackets. The third most rated aspect (rating 2.6) was the unclear behaviour of the tool, which in some instances appeared as a "black box". The absence of an optimisation engine did not seem to be a major concern.

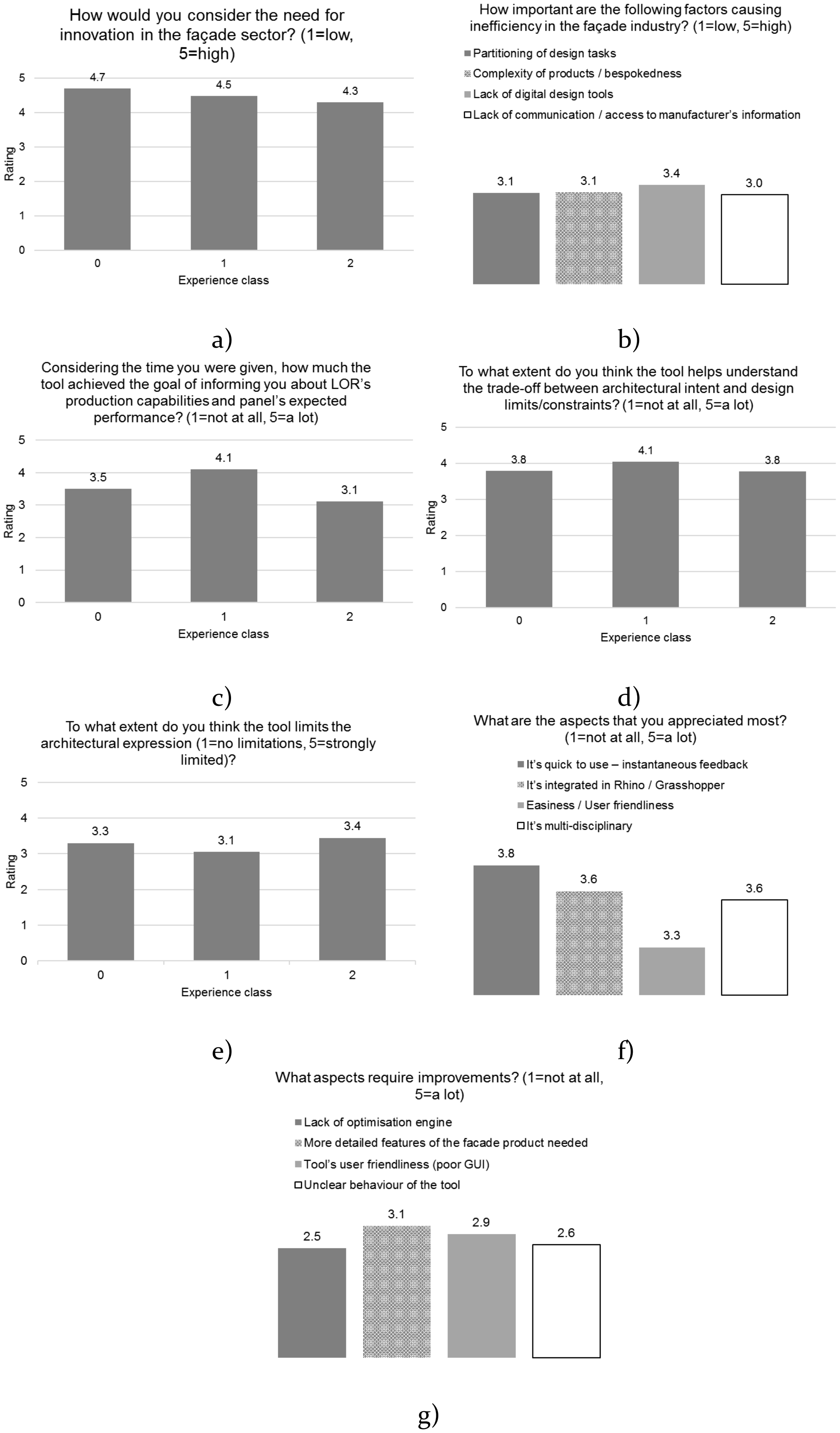


Figure 33: Results from the survey

5.2.4 Discussion

Discussion of the results from the exercise and survey

The participants concluded the design task with different degree of success: consultants with medium experience in the façade sector (from 2 to 5 years) obtained the highest final score. In particular, it appeared that the intermediate-experience group was able to control the performance of the panel with the highest ease (e.g. U-value or weight) and to limit the degree of "disruption" to the architectural intent than other groups. This evidence could be explained by the lack of experience for group 0 (experience < 2 years) and the average lack of confidence towards digital tools in general for class 2 (≥ 5 years).

All participants showed the same ability to go through the build-up configuration and in understanding the hierarchical edge bundle and how constraints should be evaluated and corrected.

The survey revealed a general agreement that the façade sector needs innovation (question a in Figure 33). The first answer to question b in Figure 33 was "lack of digital tools": this shows a possible bias (e.g. acquiescence). This evidence might be motivated by the initial introduction about the tool and the context within which the research was sitting, which was however necessary. All participants awarded high scores to perceived effectiveness of the tool (questions c and d in Figure 33) in terms of informing the user about the product manufacturability and potential to understand trade-offs between architectural intent and manufacturing limits. The tool is however deemed by the participants to create potential limits to the architectural expression (questions e in Figure 33).

The instantaneous feedback provided by the tool, its integration into an existing platform and its multi-disciplinary nature are the aspects most valued by the participants (questions e in Figure 33). These aspects have also emerged from informal conversations with the participants after the workshop. Participants found the lack of detailed features and the GUI (graphical user interface) the two main aspects to be improved further (question g in Figure 33): some participants, in fact, also manifested some concerns about the tool acting like a "black-box".

Limitations of the study

This real-world workshop and survey performed in this study has some limitations which need to be addressed in the future. First, the small sample size (32 participants) made it difficult to extend the results to other companies and tools, thus limiting the validity of the study. Moreover, since the workshop involved a small group of professionals, it was not possible to create a control group. In fact, control groups did not feature in the available literature or similar studies either. However, future efforts should include studies on a larger scale that include a control group that perform a design task without the tool support. The design task should comprise standard tools such as a laptop and internet access and allow for a longer timeframe. Moreover, it was not possible to book the workshop with the 5 companies without introducing the topic and therefore without including an underlying bias (e.g. acquiescence). In some cases, the request for a preliminary outline of the workshop came from the company itself, thus introducing an additional unknown to the problem. However, sending material beforehand is a commonly-adopted procedure for informing the participants and the whole company about the workshop content and benefits. In other cases, the workshop was booked after meeting a representative of the company at a conference after the research was shown. Finally, the limited availability of the participants has constrained the scope of the exercise, which would require more time and resources: although all participants managed to conclude the exercise to different degrees of success, it would be preferable to extend the domain of the exercise beyond one hour in order to faithfully replicate a real-world design task.

Estimated benefits from the adoption of the digital tool

The lack of a control group has made it difficult to assess the extent to which the digital tool improves the daily routine design. To this end, Table 12 shows an estimation of the time required to perform hand calculations in lieu of those performed by the tool. To the best of the authors' knowledge, there is no metric available in the literature for calculating each single task in Table 12, and therefore it was compiled by the author based on their experience. Based on the outcome, it is reasonable to assume 1h would be sufficient to complete the configuration with the tool in this instance. The tool is therefore four times quicker than traditional hand calculations, thereby generating a time saving of approximately 4 hours. The non-value adding time (i.e. time to retrieve information) is not present in the tool's usage since the required information / knowledge is directly embedded into the tool.

Table 12: Estimated time to perform the tasks performed by the digital tool (based on the authors' experience, with average time for an email with answer = 6h, and average basic time for searching an information = 0.25h)

Task	**Estimated value-adding time for the task (h)**	**Estimated non-value adding time to retrieve required information (h)**
Area-weighted U-value calculation (incl. thermal bridges)	0.5h	0.25h
Embodied carbon calculation (incl. linear elements)	0.5h	0.25h
Daylight factor calculation	0.1h	0.25h
Overall thickness calculation	0.1h	0.25h
Overall weight calculation	0.25h	0.25h
Structural concrete thickness calculation	1h	0.25h
Compliance to standard constraints checking	18 constraints x 0.1h / constraint = 1.8h	1 email = 6h
Bracket type (standard VS bespoke? If standard, which type?)	0.5h	1 email = 6h
Σ	4.75h	13.5h

Additional time is then required to further detail and complete the design of the panel. These design aspects (e.g. concrete rebar detailed design, specific code-compliance calculations) are not included in the table since they fall outside the scope of the tool. Although these aspects might constitute a large ratio of the overall design cost, there is another aspect to consider. Figure 34 shows how early stages play a more significant role in driving costs than later design and manufacturing stages. Early stages, in fact, embed significant "latent" costs, which is the cost of committing to a specific design option. Design decisions of this type in prefabricated façades include choosing the panel's main dimensions, the position of the horizontal joint, as well as window openings are such aspects when designing prefabricated concrete façades. Therefore, the value of using such tool should in fact be significantly larger than the time saving in pure "actual costs". The benefit of committing to a lower cost option at early design stages should also be included.

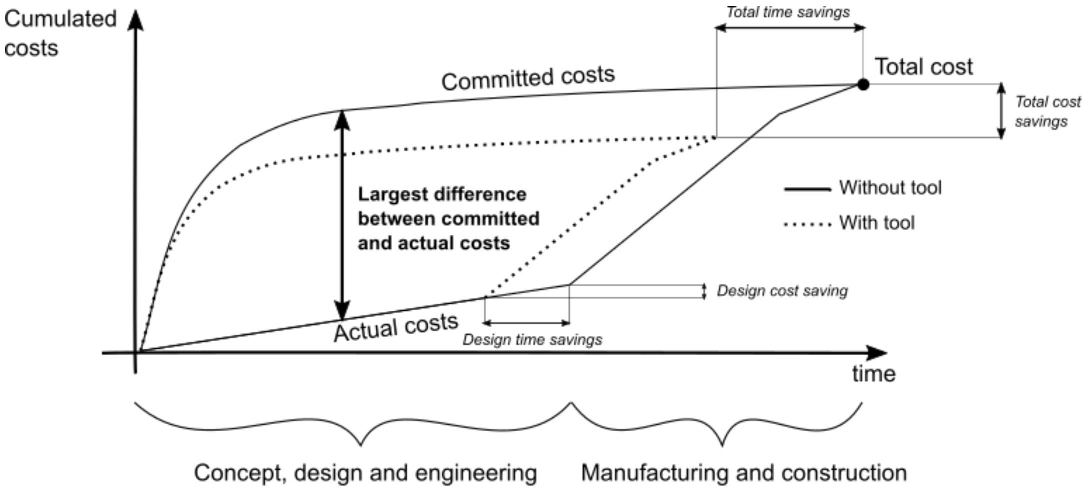


Figure 34: Committed and actual costs during the design & construction stage (adapted from [92]). The digital tool acts on early stages, where the difference between committed and actual costs is larger

The additional benefits that should be included in the calculation of the tool can be defined by assessing risk. The risk associated with the construction stage, and even the life-service (e.g.: overheating / glare risk), includes a series of unforeseen / unwanted design errors that might constitute additional costs for the contractor. Thus, the use of a tool that informs about possible "unfeasible" and unwanted design choices earlier in the design stage could lead to risk reduction. A realistic value of risks, normally used at bid stage, would be between 3% and 5% of the façade package. Thus, if the package for a precast concrete façade is £ 1M, the value of the perceived risk by the contractor through a normal design and construction process ranges from £ 30k to £ 50k. Considering and mitigating the risks reduce the risk exposure of the contractor and reduce costs for the client. Certain design and construction stakeholders (e.g. contractors and subcontractors) normally set de-risking the project as the major priority; a project that is deemed to be high risk will deter some contractors and subcontractors from bidding altogether and thereby reduces competitiveness.

Another potential benefit is the reduction in manufacturing cost. Labour and material cost drive a large ratio of the final product's costs (approximately 68% [84]) and therefore large savings can be generated by increasing the level of unwanted bespoke features (by definition, the most manufacturable solution is the one with the lowest cost [93]). Hence, for a £ 1M package for a precast concrete façade, approximately £ 680k are material costs[6]. The potential savings obtained from shifting toward more DFMA-preferable options are therefore another benefit that could potentially arise from the use of the tool. Again, quantifying such benefits to a higher degree of precision is challenging.

5.2.5 Conclusion

The present study has shown a testing campaign for a software tool aimed at supporting designers and consultants during the initial configuration of a specific façade system. The software was tested with five UK-based engineering consultancy companies, with 32 people participating overall. Four quantitative indices have been defined to assess the "goodness" of the design solutions generated by the participants with the aid of the tool. The indices measure the

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[6] In reality, "material cost" can include labour, depending on the stakeholder: as an example, a precast concrete façade manufacturer that purchases steel bracketry from a supplier will place this item under the voice "material cost". The supplier, in turn, will consider bracket costs as broken down into both material (steel) and labour (e.g. welding, cutting operations). In the above considerations, we assume that material costs include labour.

tool's usability / configuration easiness, control of façade panel's performance, compliance to manufacturing- and performance-related constraints, and how the tool usage interferes with architectural design. A survey about the need for integrated and digitalised approaches was then completed by the participants.

The results from the exercise and the survey showed how groups with average façade design experience (2 to 5 years) appeared to perform better than other groups. The aspect in which these groups performed best was in the ability to control the façade performance digitally without excessively altering the architectural design. This evidence could be explained by the ability of these groups to deal with digital tools during their daily routine, while having a sufficient understanding and experience of façade design. The validity of the conclusions is limited to the participants and the tool under investigation. There are in fact a number of limitations that should be overcome to fully understand the real benefits arising from such a new approach.

Successive studies should conduct larger-scale analyses to confirm the above results and to better understand how currently-available tools might affect designers and consultant's activities. The creation of a baseline or control group, to evaluate the traditional approach towards façade design, would be also needed.

Finally, an analysis of the potential benefits arising from the use of the tool was made. It was first shown that the tool can potentially reduce design times by a factor of four. Then, a series of future costs, of which early design stages are responsible (namely, risk and manufacturing costs), were estimated. It was shown that, despite the approximate nature of these cost estimates, the tool could potentially reduce the global façade costs.

5.3 Validation 2: Tool demonstration on two real-world projects

5.3.1 Introduction

The capability of the digital tool to support internal bidding processes of a façade contractor for precast concrete panels was tested on two real-world projects. The projects are commercially confidential and the non-technical details that are not relevant for this study are not disclosed here. The tool was used by the author by working alongside the façade contractor.

The following procedure was adopted to use the tool: after receiving the design documents (frontal view of the proposed façade), the main geometrical features (width, height) were extracted and implemented into the tool. The tool returned the “enriched” design solution, including expected weight, embodied carbon, U-value, thickness and type of insulation, as well as compliance to a set of design and manufacturing constraints. This additional information was then used at project meetings. The process flow is akin to that shown in Figure 22, when the manufacturer uses the tool to provide feedback on the architectural design during early-design stages.

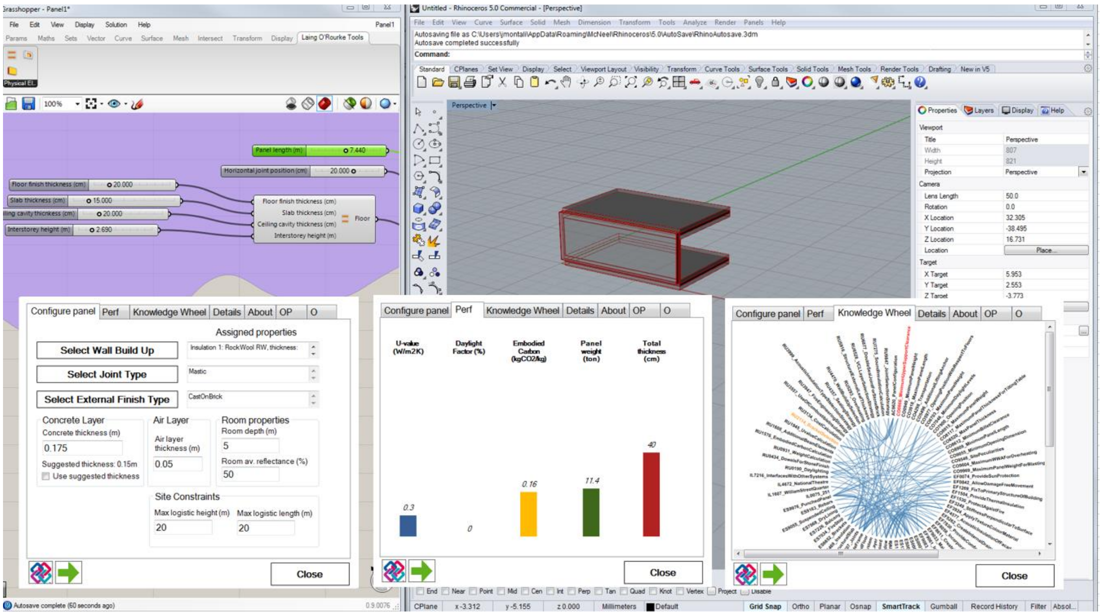
5.3.2 Project A: manufacturing challenges

Description of the project

Project A is a shopping centre in London, whose cladding options include single-skin concrete precast panels. The façade manufacturer participates on a pre-construction service agreement (PCSA), to give early-stage feedback on the cladding options in terms of manufacturability and expected performance. The architectural design included two panelisation schemes (upper image of Figure 36 and Figure 37) that were then evaluated by the contractor for comments and by including different options. A document produced by the architects including the maximum U-value was used as a reference for the insulation thickness. The material type for the insulation was to be rockwool.

Results from the tool usage

Each façade panel constituting the panelisation scheme was analysed with the tool. A series of performance indices and broken constraints were then evaluated and reported in the format shown in Figure 36 and Figure 37.



Panel length (m) 7.440
Horizontal joint position (cm) 20.000
Floor finish thickness (cm) 20.000
Slab thickness (cm) 15.000
Ceiling cavity thickness (cm) 20.000
Interstorey height (m) 2.690

Assigned properties
Select Wall Build Up: Insulation 1: RockWool RW, thickness:
Select Joint Type: Mastic
Select External Finish Type: CastOnBrick

Concrete Layer
Concrete thickness (m): 0.175
Suggested thickness: 0.15m
☐ Use suggested thickness

Air Layer
Air layer thickness (m): 0.05

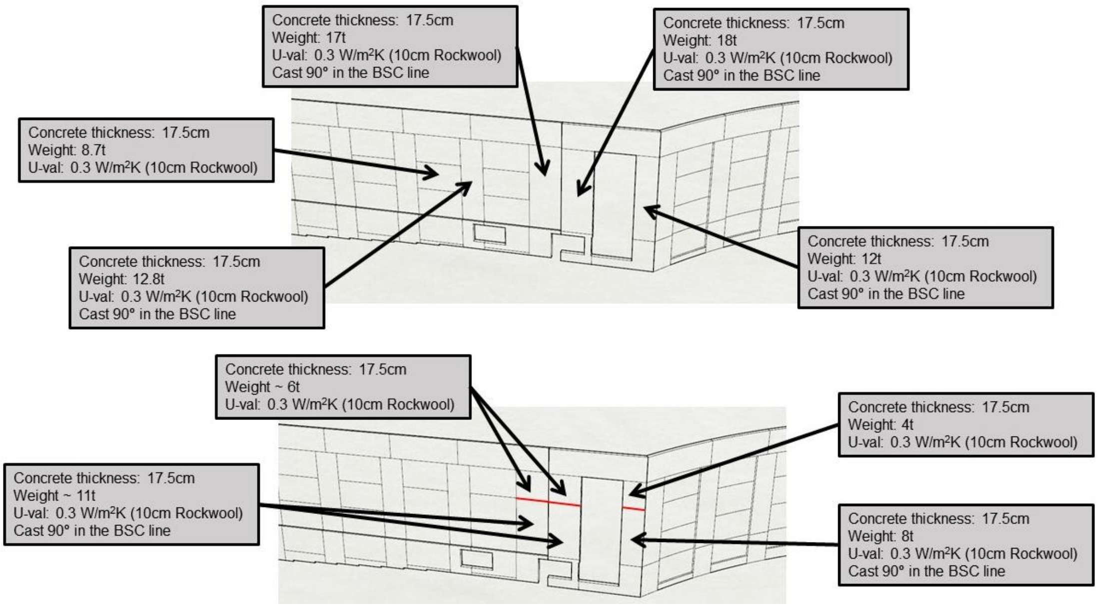
Room properties
Room depth (m): 5
Room av. reflectance (%): 50

Site Constraints
Max logistic height (m): 20
Max logistic length (m): 20

U-value (W/m2K): 0.3
Daylight Factor (%): 0
Embodied Carbon (kgCO2/kg): 0.16
Panel weight (ton): 11.4
Total thickness (cm): 40

Autosave complete (60 seconds ago)

Figure 35: Example of output from the analysis of a single façade panel. From left to right at the bottom of the image: configuration, performance and compliance to broken constraints tab


Concrete thickness: 17.5cm
Weight: 17t
U-val: 0.3 W/m²K (10cm Rockwool)
Cast 90° in the BSC line

Concrete thickness: 17.5cm
Weight: 18t
U-val: 0.3 W/m²K (10cm Rockwool)
Cast 90° in the BSC line

Concrete thickness: 17.5cm
Weight: 8.7t
U-val: 0.3 W/m²K (10cm Rockwool)

Concrete thickness: 17.5cm
Weight: 12.8t
U-val: 0.3 W/m²K (10cm Rockwool)
Cast 90° in the BSC line

Concrete thickness: 17.5cm
Weight: 12t
U-val: 0.3 W/m²K (10cm Rockwool)
Cast 90° in the BSC line

Concrete thickness: 17.5cm
Weight ~ 6t
U-val: 0.3 W/m²K (10cm Rockwool)

Concrete thickness: 17.5cm
Weight: 4t
U-val: 0.3 W/m²K (10cm Rockwool)

Concrete thickness: 17.5cm
Weight ~ 11t
U-val: 0.3 W/m²K (10cm Rockwool)
Cast 90° in the BSC line

Concrete thickness: 17.5cm
Weight: 8t
U-val: 0.3 W/m²K (10cm Rockwool)
Cast 90° in the BSC line

Figure 36: Project A, panelisation option 1. Upper image: proposed solution, lower image: adjusted solution with added jointing solution for logistic reasons. The red line represents an additional panel division due to logistic reasons

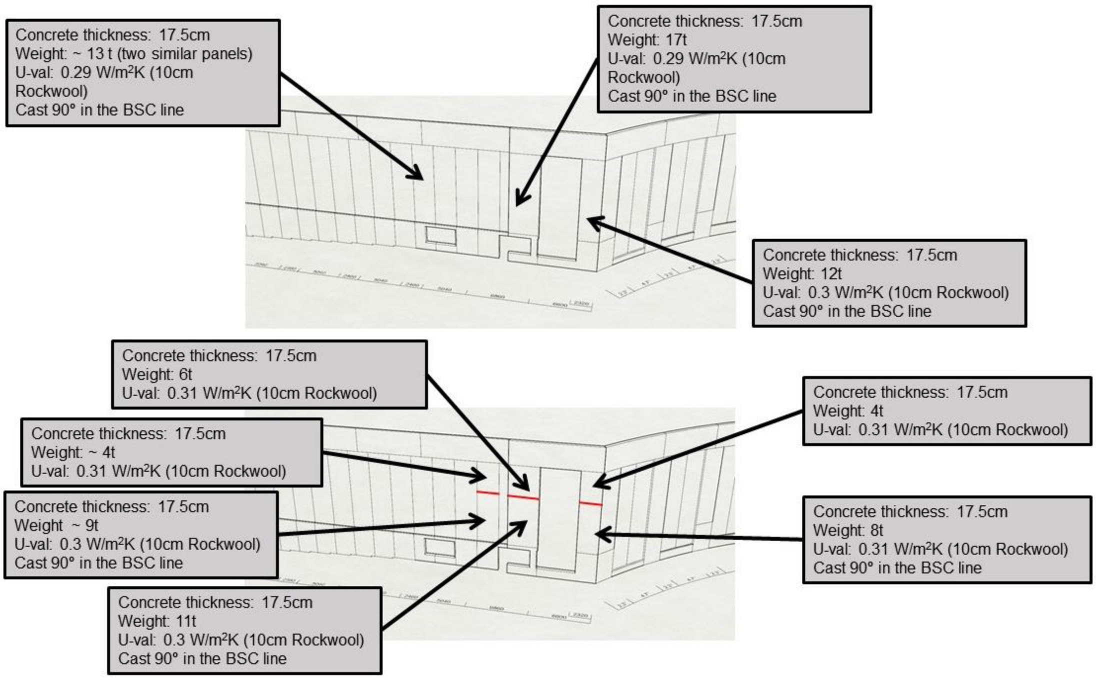


Figure 37: Project A, panelisation option 2. Upper image: proposed solution, lower image: adjusted solution with added jointing solution for logistic reasons. The red line represents an additional panel division due to logistic reasons

The analysis led to the following conclusions: first, a façade concrete thickness of 17.5 cm was determined by applying the case-based formula described in section 4.3.2. Then, the insulation thickness (whose type was set to rockwool) was chosen to meet the maximum U-value target, which included the incidence of thermal bridges. Performance indices and broken hard and soft constraints were then evaluated. In both panelisation options, the panels met the target U-value, which was given by the contractor. Due to the large height/width ratio, some panels had to be rotated by 90° than normal to fit the casting steel pallet in the "bespoke carousel system" line (section 4.2.2). The different casting orientation also requires additional lifting anchor along the long edge of the panel and a steel turning shoe for additional turning operations onsite. The overall result is additional onsite operations and material costs.

The tool raised also some issues concerning the weight of the panels, which exceeded the maximum weight for lifting operations in both options. For this reason, an adjusted solution that split exceedingly heavy panels was proposed by the contractor and validated by the tool (bottom images in Figure 36 and Figure 37).

The overall time taken to produce the output shown in Figure 36 and Figure 37 was approximately 2 hours (18 panels), including the production of the final reports.

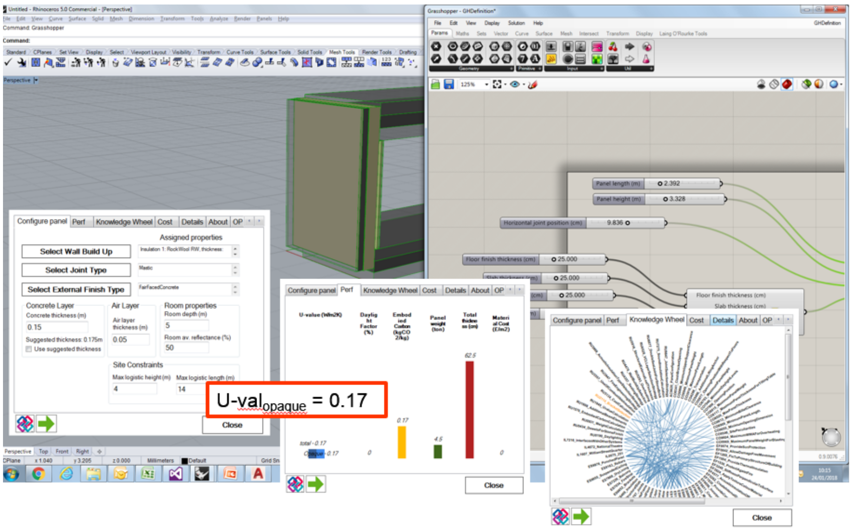
5.3.3 Project B: design challenges

Description of the project

Project B is a residential project in London. The investigated façade was a single-skin precast panel located at the first three floors of the building. The documentation provided was a panelisation scheme on various orientations and a document stating the thermal requirements of the façade. There is a very stringent limit, provided by the MEP engineers, on the U-value of the opaque elements (0.15 W/m^2K including thermal bridges). The insulation type was already chosen to be rockwool.

Results from the tool usage

The tool was used to analyse the single panels and their thermal requirements, as well as the compliance with the manufacturing constraints. In general, there were challenges in achieving the 0.15 W/m^2K limit without using exceedingly high insulation thicknesses. An initial, tentative value of 30cm was assumed and, as shown in Figure 38, in some instances (depending on the length of the linear thermal bridges) it was not possible to comply with the imposed limit on the U-value. An alternative solution with polyurethane-based insulation was therefore also evaluated. A total number of 12 solutions was analysed in 4 hours, including a design change and the production of the output documentation.



-30 cm Rockwool + 5cm acoustic insulation to achieve 0.15 W/m^{2}K <u>not enough</u> (including point and panel-to-panel thermal bridges and +10% increase due to uncertainty)

- undetermined bracket

- suggested concrete thickness: 17.5 cm (15cm used)

Figure 38: Type of output produced for Project B. In a similar way to what done in Figure 36 and Figure 37, the provided output consisted of a screenshot of the tool's GUI and some side comments

5.3.4 Discussion

The analyses conducted on two real-world projects show how the proposed digital tool can constitute a valuable, early-stage solution during the bidding process, which is known to have a large influence on the façade contractor's operational costs and construction-related risks. The application of the tool to project A led to the creation of a proposal for an alternative panelisation scheme, by introducing a joint for logistic purposes as well as by defining the insulation thickness. The insulation thickness was determined based on the length of the linear thermal bridges, which in turn determined the overall thermal linear loss through the building envelope. Project B showed challenges in the definition of the insulation thickness, while controlling a series of manufacturing constraints.

5.4 Conclusions

In this chapter, the tool was tested in both a simulated environment / laboratory (workshops with consultants) and in an operational environment (use of the tool for supporting bidding operations). Both tests showed that the time required to perform routine calculations was significantly reduced: in the first case, by a factor of four and, in the second case, by analysing both thermal requirements and manufacturing aspects of 30 different precast façade panels in approximately 6h. In addition, an approximate cost analysis was performed to show that the tool, apart from achieving “instantaneous” design cost savings, can potentially optimise the majority of the expected future costs (risk and manufacturing).

In the workshop with the façade consultants, participants were asked to “optimise” the design solution by modifying the product model manually, while keeping the original architectural intent as intact as possible. In the next chapter, we will build upon this aspect by adding an automated optimisation layer in the digital tool via specific optimisation techniques.

Chapter 6

Fully-automated façade design

6.1 Introduction

Chapter 5 has shown the validity of the tool and that is a valuable resource for early-stage design processes. The tool in chapter 5 required the users to manually search for the optimal configuration while designing and obtain feedback, from the tool via the GUI, including performance indices and compliance with manufacturing constraints. The user would then modify their configuration in response to this feedback. In doing so, the user subjectively explores the adequacy of each façade solution within the domain of possibilities in a search for an optimal solution. The architectural intent, representing the aesthetical expression of the façade product, was inherently achieved by modifying the product model to the desired configuration. This chapter investigates ways of automating the use of the digital tools to assist in the search for the optimal configuration between a set of optimal options to meet both performance- and architecturally-related criteria, while respecting a set of design & manufacturing constraints. Computational optimisation techniques will be used for this purpose. The first part of this chapter provides a background to optimisation techniques and optimisation in façades; this is followed by a methodology for targeting the above three aspects. The methodology is subsequently tested on a real-world case study. The chapter concludes with final remarks and the answer to SRQ5.

6.2 Optimisation in façades

6.2.1 The optimisation problem

Optimisation is a technique aimed at determining the minimum or maximum value of a specific function, while respecting a series of constraints. The function can be either explicitly defined in analytical form or unknown (in case of "black-box" approaches). Depending on the number of objectives, an optimisation problem can be either single-criterion or multi-objective. A single-objective, constrained optimisation problem can be expressed as:

$$minz(x) \tag{3}$$

While:

$$g_i(x) \leq 0 \qquad i = 1, \ldots, n \tag{4}$$

$$x_j \geq 0 \qquad j = 1, \ldots, m \tag{5}$$

where $z(x)$ is the objective function to be minimised, $g_i(x)$ is a set of constraints and $x = (x_1, \ldots, x_i, \ldots, x_n) \in R^n$ is the vector of the variables or parameters of the problem. The solution of the optimisation problem defines a "feasible region" X [95], which respects the above constraints:

$$X = \{x : x \in R^n, g_i(x) \leq 0, x_j \geq 0\} \tag{6}$$

The optimal solution is the vector $x \quad \in X$ that minimises $z(x)$. $g_i(x)$ defines the set of constraints from the design and manufacturing domains, such as:

- thermal transmittance: $U_{façade} \leq U_{max} \longrightarrow g_1 = U_{façade} - U_{max} \leq 0$
- bending resistance: $M_{rd} \geq M_{Ed} \longrightarrow g_2 = M_{Ed} - M_{rd} \leq 0$
- overall façade dimension: $d \leq d_{max} \longrightarrow g_3 = d - d_{max} \leq 0$

Other types of constraints can be logical rules such as IF…THEN… which can be captured, for instance, from manufacturing knowledge. Similarly, a multiobjective problem, i.e. a problem with many functions to be optimised, such as that of a realistic façade engineering design problem, can be expressed as:

$$minz(x) \tag{7}$$

where $z(x) = \left[z_1(x), \dots, z_p(x)\right]$ is the vector of objective functions and the feasible region X is defined by equation 4, based on constraints from equations 2 and 3. The problem introduces a sub-set $\boldsymbol{S} \in X$, called set of non-dominated solutions, where, for every solution in the complementary set $Q = X$, there is a solution in $\boldsymbol{S}$ that improves, or equals, at least one of its objective and one (still in $\boldsymbol{S}$) that improves all its p objectives. The set of non-dominated solutions (Figure 39) can be defined, for a minimum problem, as:

$$\begin{aligned} S = \{x\colon x \in X, \nexists\, x' \in X : z_q(x') < z_q(x)\ \forall\, q \\ \in \{1,2,\dots,p\}\ z_k(x') < z_k(x)\ \forall\, k \neq q\} \end{aligned} \tag{8}$$

A multi-objective optimisation can be transformed into a single-criterion problem through a penalty function approach [96]. A penalty function F is defined as the linear combination between p objectives $z(x)$ and p exchange coefficients α_i:

$$F(x) = z(x)^{-1} \cdot \alpha = z_1(x) \cdot \alpha_1 + \cdots + z_p(x) \cdot \alpha_p \tag{9}$$

The total derivative of $F(x)$ is:

$$dF(x) = dz_1(x) \cdot \alpha_1 + \cdots + dz_p(x) \cdot \alpha_p \tag{10}$$

The total derivative of a generic function can also be expressed as:

$$\mathrm{d}F(x) = dz_1(x) \cdot \frac{\partial F(x)}{\partial z_1(x)} + \cdots + dz_p(x) \cdot \frac{\partial F(x)}{\partial z_p(x)} \tag{11}$$

By comparing equations 10 and 11, exchange coefficients are therefore defined as:

$$\alpha_i = \left(\frac{\partial F(x)}{\partial z_i(x)}\right)_{z_j(x), j \neq i} \tag{12}$$

Exchange coefficients represent the variation of the penalty function when objective functions $z_i(x)$ vary one at a time. The main advantage of such approach is that it is possible to reach a unique optimal solution, whereas the drawback is the difficulty of selecting appropriate exchange coefficients, which can be prone to a degree of arbitrariness. For example, a possible situation is when the trade-off between initial cost and operational energy of a façade is analysed. Life performance is usually represented by annual energy consumption calculated through a building energy simulation [97], where energy is defined on an hourly basis over a representative period (e.g. typical meteorological year, TMY [98]). In this case, the penalty function is expressed as:

$$F = C \cdot \alpha_1 + E \cdot \alpha_2 \tag{13}$$

Where C is the initial cost of the façade (£), E is the energy consumption (kWh) over a representative period (e.g., 20 years) and α_1 and α_2 are the relevant exchange coefficients. If F is the sum of the initial and operational costs during the life cycle of a façade, then $\alpha_1 = 1$ and α_2 represents the average cost per kWh of energy consumed (£/kWh) over the period of investigation. Equation 13 can be rewritten as:

$$C = -E \cdot \alpha_2 + F \tag{14}$$

Equation 14 defines a set of parametric, parallel curves (C_i in Figure 39) where $-\alpha_2$ represents the slope and F the intercept. The optimal solution x is the combination of variables that returns $z_1(x)$ and $z_2(x)$ so that the curve is tangential to the Pareto front. The optimal solution is very sensitive to the values of the exchange coefficients: if α_2 is low (i.e. low cost of energy), E will be more heavily penalised and the optimal solution will shift to more low-cost and high-energy consuming façades (C_i curves in Figure 39 have a lower slope). Different exchange coefficients can be introduced for assessing the impact on cost of carbon emissions, maintenance requirements or daylight levels, therefore transforming the multi-objective optimisation into a p-dimensional problem.

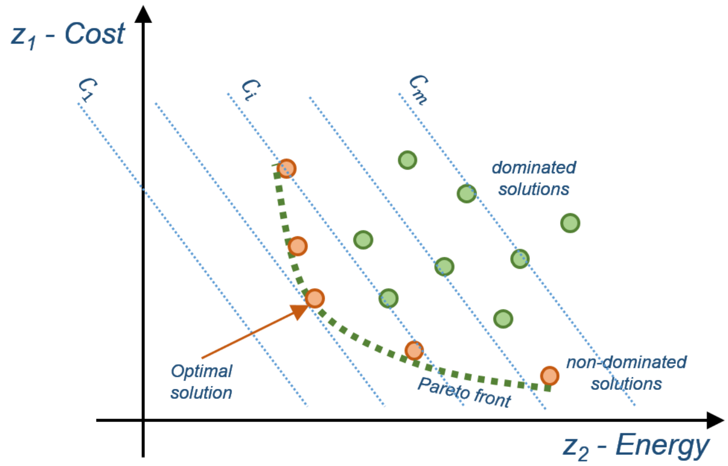


Figure 39: Dominated, non-dominated solutions and optimal solution (adapted from [96]*)*

6.2.2 Optimisation in façades

The application of optimisation in façades follows the above-mentioned approach. Once objective functions and constraints are selected, the optimisation problem is constructed and the optimal solutions are investigated. To determine the optimal solutions, specific algorithms are required. Jin [99] reviewed alternative methods and summarised their pros and cons, for the optimisation of a façade system in terms of whole-life value (WLV). Genetic Algorithms (GA) were found to outperform others due to its ability to find the global minimum and to manage various objectives and constraints. GA is the basis for the façade multi-objective optimisation tool development currently part of the research activity within the Glass and Façade Technology Research Group [100]. The tool (Figure 40 - [99]) optimises different objectives such as energy performance, thermal comfort, carbon emissions or cost, but it currently does not support knowledge storage and reuse and it relies on generic parameters, such as window-to-wall ratio, thermal transmittance and parametric costs: in this way, non-manufacturable solutions are not excluded from the optimisation process.

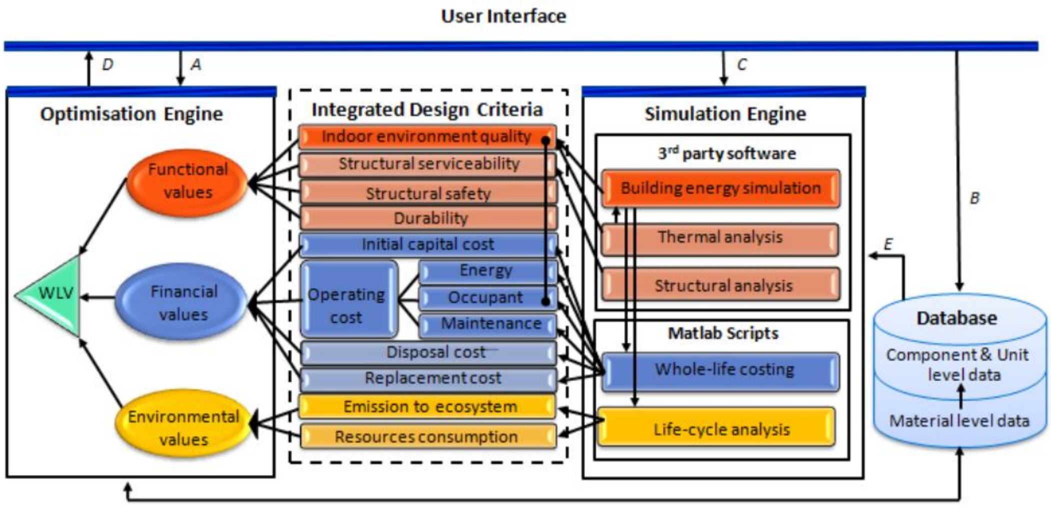


Figure 40: Whole Life Value multiobjective optimisation system [99]

Moreover, the use of optimisation in the façade sector still faces major obstacles. A recent interdisciplinary study conducted by Innovate UK has shown that the AEC sector still finds it difficult to apply optimisation in normal design routine, despite opportunities exist [24]. In a recent conference ("Advanced building skins 2017") some large design consultancy companies are starting to apply simple optimisation approaches to façade design, but the effort is therefore limited to companies with specific capabilities and size and it does not present a specific rationale that can be shared amongst sector professionals and academics.

The challenges arising from the use of GA optimisation in façades has been investigated in a SWOT (strengths, weaknesses, opportunities and threats) table (Table 13). What emerges is that more design & manufacturing knowledge should be added to the optimisation problem. In addition, GAs can take significant computational time (several hours), which is not aligned with the timescale of design iterations (even few minutes). Third, the architectural intent should be included as a design criterion, given its importance in the final design. Finally, more general-purpose and less mathematically-oriented programming languages should be used to implement the optimisation into the current design software packages. The following section will introduce a methodology to target the above-mentioned weaknesses.

Table 13: SWOT analysis of the use of GA optimisation in façades

	Helpful	**Harmful**
	Strengths	**Weaknesses**
Internal origin	The algorithm achieves very precise solutions Widely used and known in the academy for many engineering problems	Solutions are normally poorly constrained GA can take long time to run Architectural intent as an objective is not considered Need for specific mathematical languages (e.g. MATLAB, Python), which are poorly integrated in current design software (e.g. Rhino, Revit, Sketchup)
	Opportunities	**Threats**
External origin	Scarcely applied to façade sector except from academic research and one-of-a-kind applications from large companies	Reluctance to adopt it in real-world applications

6.3 A knowledge-richer technique for façade design

A novel multi-objective optimisation is here developed to determine the optimal trade-off between 1) the architectural intent and 2) the required performance, while taking into account a series of 3) constraints. The three elements are explored in a so-called "meta-domain" and they are represented by a scatterplot (Figure 41b). The idea is to automatically generate a relatively large number of solutions starting from the solution initially conceived through the knowledge-based tool (here defined as "proposed design") and to identify the optimal ones by applying small variations from the proposed design.

The X-axis in Figure 41 represents the architectural intent, which, for the purpose of this study, is defined as the variation from the "proposed design" in terms of main frontal geometrical features (e.g. joint and openings position and dimensions). This is based on the hypothesis that early-stage architectural intent is mostly driven by those features. Therefore, the index named "Variation from proposed design" of the *i-th* solution d_{i1}, obtained in a similar way to the concept of variance in statistics, is defined as:

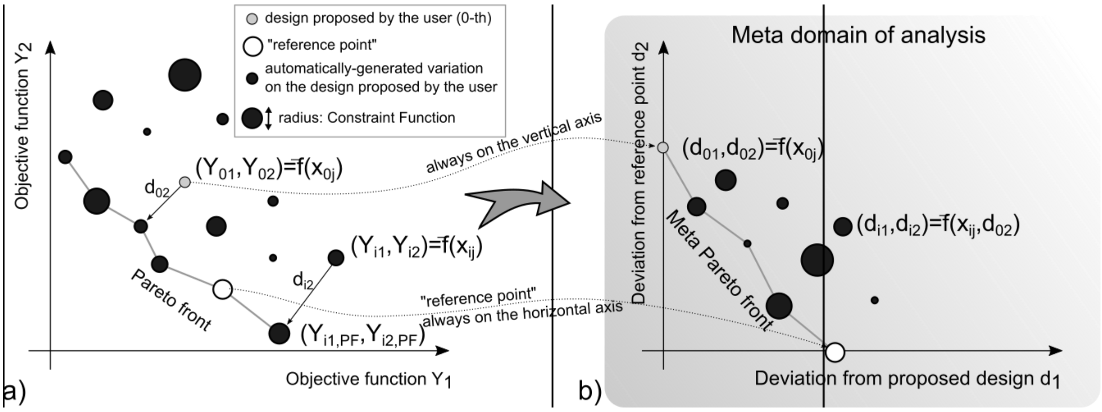


Figure 41: traditional domain of analysis in optimisation (a) and proposed "meta-domain" (b) for the optimal selection of the conceptual solution by considering the design intent

$$d_{i1} = \sqrt{\sum_j^N \left(\left(x_{ij} - x_{0j}\right) \cdot 100/x_{0j}\right)^2 / N} \tag{15}$$

Where x_{ij} is the *j-th* frontal geometrical feature of the *i-th* solution generated by the optimisation engine and x_{0j} is the *j-th* frontal geometrical feature of the proposed design. Small values of d_1 represent solutions that preserve the initial architectural intent, which is intrinsically embedded in the proposed design.

The Y-axis represents the required performance, defined as the deviation of the *i-th* solution from a "reference point", defined below. The index, named "Deviation from the reference point" of the *i-th* solution, d_{i2}, is defined as:

$$d_{i2} = \sum_k \left(\alpha_{ik} Y_{ik} - \alpha_{k,PF} Y_{k,RP}\right) \cdot A_{tot}/A_{panel} \tag{16}$$

where Y_{ik} is the value of the *k-th* objective function associated with the *i-th* solution, $Y_{k,RP}$ is the value of the *k-th* objective function associated with the point, on the Pareto Front, representing the optimal choice (the "reference point"), A_{panel} is the area of the façade panel and A_{tot} is the total area covered by the façade type under investigation. d_{i2} is always defined as positive since $\alpha_{k,PF} Y_{k,RP}$ is the smallest of all $\alpha_{ik} Y_{ik}$. The reference point can be found by creating a penalty function P [96], which coincides with the value of d_{i2}. Therefore, α_k represent the exchange coefficients (as described in section 6.2.1) that describe how the penalty function varies with each the objective functions ($\alpha_{ik} = \partial P/\partial Y_{ik}$). The coefficients can be either constant or variable. The ratio

A_{tot}/A_{panel} represents the total number of panels. A small d_2 indicates that the expected performance of the solution is close to optimal.

The radius of the *i-th* point on the scatterplot represents the number of knowledge-based constraints which are violated. Depending on the level of importance of each constraint, its violation can be either classified as an error (hard constraint), or as a warning ("softer" constraint). The information on whether a violated constraint is hard or soft is contained in the KB. For example, a constraint is hard if the weight of a façade panel exceeds the transportation limits, whereas the constraint can be deemed soft if a rule-of-thumb indicates a higher risk of failure (e.g. window-to-wall area above a certain limit for overheating risk, thus requiring further detailed, specialist analyses). The importance of constraints violated in each façade solution is summarised by the "weighted constraint score" (WCS) as defined below. Furthermore, since it is desirable to have the "virtuous" solutions (i.e. solutions with few violated constraints) to be more visible in the scatterplot, an index, named "constraint function" (CF) and representing the radius of the *i-th* point, is defined as follows:

$$CF_i = -a \cdot WCS_i + b \tag{17}$$

$$WCS_i = A \cdot NumOfErrors + B \cdot NumOfWarnings \tag{18}$$

where a and b are coefficients to visualise the radius of the *i-th* point, and A and B are coefficients that assign weights to errors and warnings, respectively. A and B are equal amongst all solution and they are characterised by a certain level of discretion: as an example, one could assign A = 1 and B = 0.5 to indicate that errors are assigned a weight if twice that of the warnings. Maximising the constraint function CF means minimising the number of violated constraints (represented by the WCS) and simultaneously making the solution more visible in the diagram by increasing its radius (represented by the *CF*).

The goal of the optimisation is therefore to minimise both d_1 and d_2, while maximising CF. If the "proposed solution" is the optimal one, then it will have coordinates (0,0) in Figure 41. If no solution is found at coordinates (0,0), a set of non-dominated solutions ("meta-Pareto front") will be generated that consider a trade-off between architectural intent, deviation from the reference point, and number of violated constraints represented by *CF*. This approach is effective when implemented with interactive data visualisation techniques such as HTML diagramming with the Javascript Library D3.js [89], due to the large amount of data that is generated.

Figure 42 shows a possible use of the proposed process in an early-design stage. The diagram is drawn in BPMN [28], a domain-agnostic and generic notation used for modelling processes. This diagram can be seen as a subcategory of the process maps described in section 3.4. The process allows the user to generate their own conceptual design, then enrich it with the knowledge-based tool, evaluate the performance and check if the design complies with the production-related constraints. Then, the user may either repeat the process normally to remove constraints that are violated or he/she chooses to run the computational optimisation to look for alternative high-performance, constraint-compliant solutions.

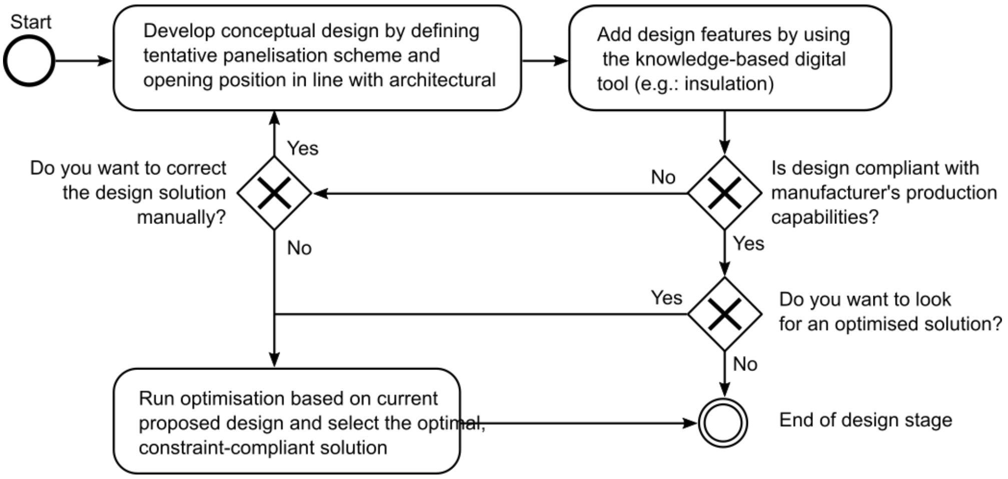


Figure 42: Proposed "enhanced" design process, in a BPMN notation, at conceptual stage incorporating optimisation by using custom-built digital tools

6.4 Application to a case-study

The case study consists of a recently built residential building in London. The tower is a 36-storey building clad with precast, single-leaf concrete panels. The prefabricated panels include precast concrete, insulation and window elements.

The total area of the façade is 3,532m². Once the component was installed, the dry lining, vapour control layer and plasterboard were applied onsite. Figure 43 shows the panel's main frontal dimensions, position with respect to the primary structure and build-up. The south east façade is considered in this study. This case study was selected because it is very sensitive to early-stage decisions that could affect later-stage performance; also, it is very important to define the main geometrical dimensions as early as possible in the design process, due to the prefabricated nature of the panel.

The panels were manufactured at the Explore Industrial Park, a manufacturing facility located in Steetley, Nottinghamshire (UK) part of the Laing O'Rourke ltd group. The facility provides production lines with different degrees of automation for different types of products depending on their level of bespokedness. The panels analysed in this paper were manufactured in the so-called "bespoke carousel system" (BSC), which consists of a semi-automated line (Section 4.2). In the BSC, the panels are manufactured on a steel table which are conveyed through a series of stations were specific operations (e.g. mould lay-up, reinforcement and fitting installation, casting, panel turning for demoulding) are performed. Each station presents some manufacturing constraints and rules that affect the design of the precast panel.

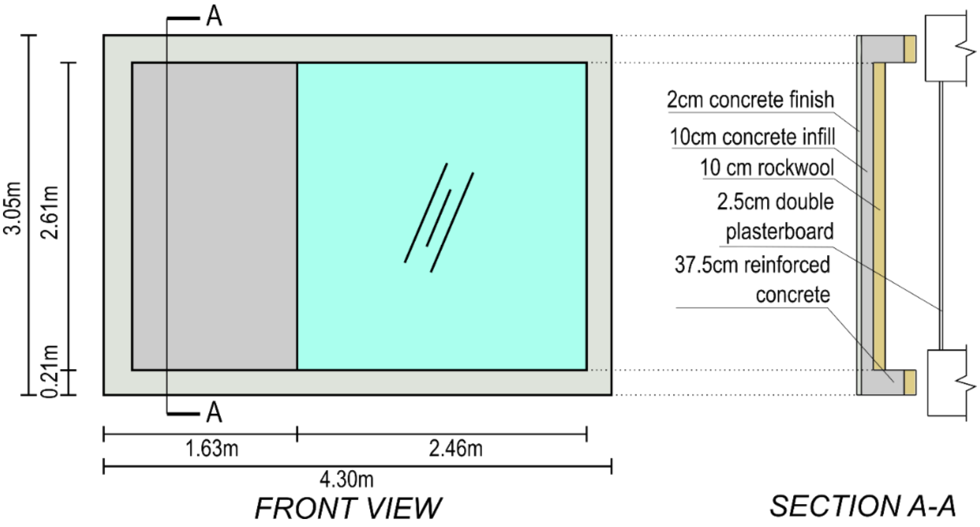


Figure 43: Main frontal dimensions (left) and build-up (right) of the investigated panel

The database assembled by the authors and used for this study comprises six types of insulation boards with different thicknesses, three types of windows (low, medium, high performance), three types of jointing materials. A knowledge-based rule governs the combination of multiple insulations (up to two) based on different criteria such as sustainability, potential installation risk from the contractor and condensation risk. Data on embodied carbon was obtained from the ICE [102] V2.0 database.

6.4.1 The optimisation algorithm

The knowledge base and the digital tool serve as configuration tools to understand trade-offs between design criteria. The approach that follows builds upon the first sub-process and seeks an optimised solution that takes into account for the optimal trade-off between performance, number of violated design and manufacturing constraints and adherence to the initially-conceived architectural intent.

The optimisation process described in section 6.4.1 was applied to identify an optimised solution. The objective functions chosen in this instance are operational carbon (Y_{i1}, measured in kgCO2/y·m^2 of floor area) and embodied carbon (Y_{i2}, measures in kgCO2/kg of panel weight). The deviation from the reference point of the i-th solution d_{i2} is therefore equal to:

$$d_{i2} = \left[\alpha_{i1}\left(Y_{i1} - Y_{i1,RP}\right) + \alpha_{i2}\left(Y_{i2} - Y_{i2,RP}\right)\right] \cdot A_{tot}/A_{panel} \tag{19}$$

The penalty function d_{i2} presents the following two coefficients α_{i1} and α_{i2}, which will be variable with the *i-th* solution:

$$\alpha_{i1} = T \cdot D \cdot L \tag{20}$$

$$\alpha_{i2} = W \tag{21}$$

where, for the specific case, T is the service life of the façade (equal to 20 years),D is the room depth (equal to 5 m), L is the panel length identifying the room width, and W is the total weight of the panel. Note that L, W, A_{panel}

andA_{tot} depend on the *i-th* solution: the digital tool will automatically calculate the value of the coefficients at runtime.

The operational energy was determined computationally by means of a building performance dynamic simulation in Energy Plus (v8.7). This involved creating a single-zone model with adiabatic surfaces except for the façade under investigation. In this model, the width of the zone corresponds to the width of the panel, which does not necessarily correspond to the room width. For this reason, the analysis should be seen as conducted over the area of influence of the façade, rather than a specific room. A "building area method" as per ASHRAE 90.1 [103] was therefore followed, in which internal gains are given for generic end uses, rather than for specific space types (e.g.: office vs open office or single office). This approach is particularly suitable for early-stage conceptual stages, where the internal distribution of spaces is poorly defined.

A custom-built, random-generating of trials algorithms was used to apply at run-time the knowledge-based network of rules and constraints and to incorporate them into the analysis. The following pseudocode describes the internal logic of the algorithm:

```
for (int i = 0; i < numOfCycles; i++)
{
        // Generate randomic variation from the proposed design, based on a maximum variation
        sibling = GenerateSibling(…,maxVariation);

        // Check if openings are not placed correctly and update number of unvalid analyses
        if (openingPositionIsCorrect(sibling) == false) {
                numOfNonValidAnalyses++;
        continue; }

        // Evaluate solution outputs
        output = EvaluateSolution(sibling);

        // Store input and output values
        UpdateOutput(sibling, output);
}
```

The algorithm iterates over a specified number of cycles (numOfCycles), thus allowing the user to control the calculation time. The algorithm generates a variation of both the frontal dimensions of the panel and the continuous variables governing the thicknesses of the internal build-up (e.g. thickness of the air layer) based on a certain user-defined "maxVariation" expressed as a percentage. Continuous variables x_i are drawn from a normal Gaussian distribution with zero mean and variance σ:

$$x_i \sim N(x_i|0,\sigma) = x_i + \sigma \cdot N(0,1) \tag{22}$$

where σ is equal to 0.5 · maxVariation, so that there is a 95% confidence interval that each sampled feature falls within the maxVariation, while allowing a 5% of outliers. The sampling was implemented via a Box-Muller transformation. Discrete variables A_j are instead sampled from a uniform distribution:

$$A_j \sim U(0,K) \tag{23}$$

Where K is the total number of discrete variables for the j-th discrete feature.

Table 14: Continuous and discrete variables governing the design of the panel. The variation of these variables has been drawn from a Gaussian and a uniform distribution, respectively

Continuous variables x_i	**Discrete variables A_j**
Panel height and width	Type of wall build-up
Relative position of panel w.r.t. primary structure	Type(s) and thickness(es) of insulation
Air layer thickness	Type(s) of window
Window(s) position within the panel	
Window(s) height and width	
Concrete infill(s) position within the panel	
Concrete infill(s) height and width	

6.4.2 Results from the optimisation

Analyses were run on a Dell Inspiron with 8GB RAM and processor Intel Core i7-3630 QM, 2.40GHz. The same optimisation was run three times with three different values for the parameter numOfCycles (150, 1500, 15000), whereas the parameter maxVariation was set to 10%. Calculation times were 8h, 2h and 20mins, respectively. The number of discarded analyses due to unfeasible geometries (e.g. window outline overlapping panel outline) was equal to 46, 473 and 4722, respectively.

The results were also compared with those obtained from a Genetic Algorithm (GA) approach, which represents the benchmark for the analyses that were run. The prototype whole-life value optimisation tool for façade design model [25] was adapted to take into account the variables and objectives in this study (all

GA-related work, i.e. the black points in Figure 44, was conducted by Dr Qian Jin at Tongji University). While the database of materials was incorporated in the GA, design knowledge from the knowledge base was not included due to commercial confidentiality. For the implementation of the genetic algorithm, a convergence test was carried out for different population sizes and numbers of generations. A population size of 1000 and number of generation of 50 was selected to ensure that a close approximation of the real Pareto front can be obtained. The crossover probability was set to 70% in the algorithm. Analyses were run on a Windows with 8GB RAM and processor Intel Core i7-4650 U, 1.70GHz. The total simulation time for the GA optimisation is 32hrs.

Figure 44 shows the results from the optimisation. Results can also be accessed at https://bit.ly/2HUEbol for an interactive view. The interactive diagram also shows the governing parameters and performance / violated constraints of every solution.

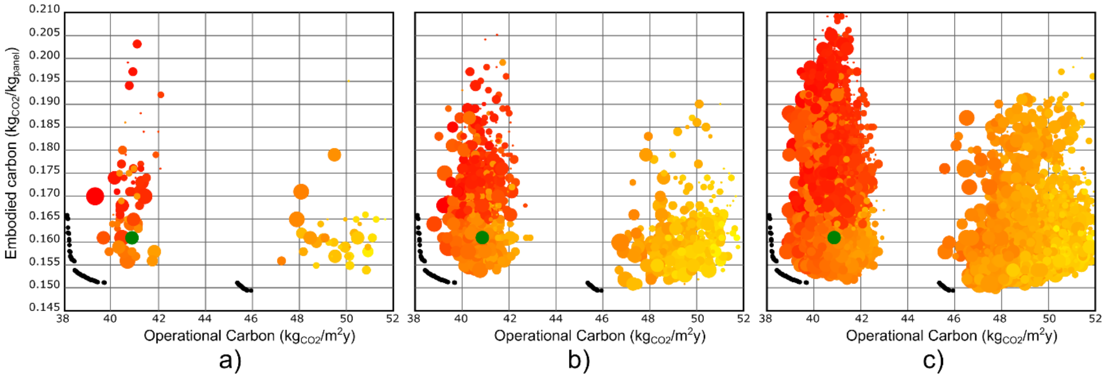
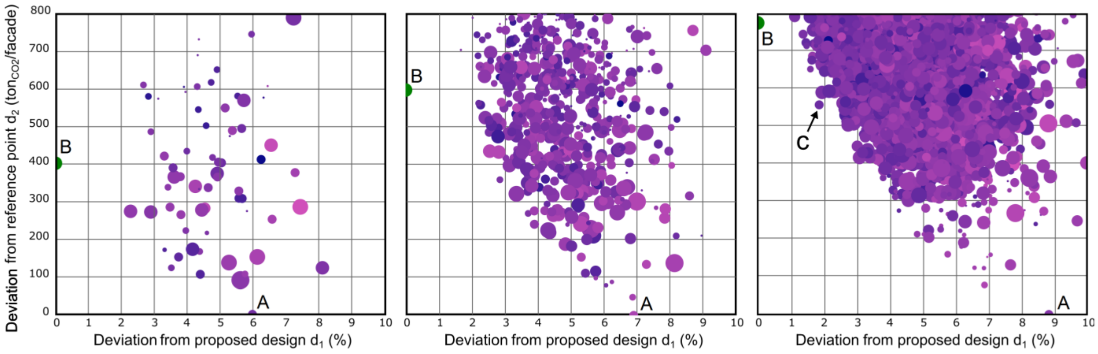


Figure 44: Results from the optimisation of the case study. Analyses for "numOfCycles" equal to 150 (a), 1500 (b) and 15000 (c). "maxVariation" was set to 10%. The colour scale from light yellow to red refers to increasing levels of overall U-value. Black points correspond to the values obtained from the GA optimisation. The green point is the original "proposed design"

Results were then elaborated and transferred to the "meta-domain" of analysis, in which the indices d_1, d_2 and CF are shown (Figure 45). The vertical axis represents the total carbon difference between the i-th solution and the reference point ($d_2 = 0$). Solutions close to the (0,0) point are both environmentally optimised and follow the initial design intent. The diagram therefore illustrates how modifying the solution towards optimality requires a corresponding modification to the original proposed design ($d_1 = 0$). Figure 45 shows the generated diagrams for the three analyses. Large radii mean low number of violated constraints in terms of performance and manufacturability. The colour represents the total thickness of the panel (increasing thickness from light to dark purple).



a) b) c)

Figure 45: "Meta-domain" of analysis for the case study, corresponding to the analyses showed in Figure 44. Analyses for "numOfCycles" equal to 150 (a), 1500 (b) and 15000 (c). The colour scale from light to dark purple refers to increasing levels of panel's total thickness. Points A and B represent the optimal solution for the two objective functions and the original proposed design, respectively. Point C represents a chosen solution which performs better than the original design

6.5 Discussion

Results shown in Figure 44 indicate that the architect's initial configuration (green circle) is not the optimal one. This is evident even if few analyses are run (150 in Figure 44a). Moreover, solutions associated with very low U-values do not constitute optimal trade-offs between embodied and operational energy: given the relatively large window-to-wall area of this study (circa 40%), the optimal solutions instead correspond to an intermediate level of specification of the window (orange). This is caused by the increased need for cooling energy in the London climate. The incidence of the window type also determined two separate groups of solutions, one corresponding to the low performance window, and one associated with the remaining two (mid- and high-performance) window types. The radii of the solutions (i.e. design and manufacturing constraints) do not follow a specific trend, but the interactive visualisation technique allows the user to browse through each solution individually. The constraints that were affected by the modifications in the range of the proposed design (maxVariation = 10%) regarded the choice of the type of structurally-supporting bracket at the bottom of the joints and the position of the opening being too close to the edge of the panel.

The average distance between the generated Pareto front and the one obtained from the GA approach tended to reduce with the “numOfCycles” parameter. In general, optimal solutions from the GA algorithm showed geometrical frontal features (panel width and height) tending towards their limits imposed for the GA optimisation.

The proposed meta-domain (Figure 45) includes the architectural intent into the decision-making process via the “Variation from proposed design” of the *i-th* solution, d_{i1}. The diagrams show two extreme points: the proposed solution (point “B”), which lies on the Y-axis ($d_{i1} = 0$ and $d_{i2} \neq 0$), and the solution (point “A”), on X-axis, that has the lowest value of d_{i2} ($d_{i1} \neq 0$ and $d_{i2} = 0$ in this case). The latter is the solution, on the Pareto front, that is geometrically more similar to the proposed design. No point with both $d_{i1} = 0$ and $d_{i2} = 0$ was determined, which corresponds to the case when the proposed solution lies exactly on the Pareto front. Table 15 summarises the values of d_1 and d_2 for these two extreme points for the three analyses. The remaining non-dominated solutions in the meta-domain represent optimal trade-offs between the whole carbon savings and the architectural expression. Non-dominated solutions thus allow for more geometrical diversity in favour of a lower environmental impact. In general, the larger the number of analyses, the larger the deviation from the reference point, and therefore the less environmentally friendly the proposed solution will be. There is therefore an additional trade-off between the computational time and the potentially-achievable carbon savings.

The proposed approach presents two distinctly novel aspects. The first is the focus on the implementation of design knowledge and its representation in interactive diagrams. This allows the user to browse through a variety of different solutions and understand their performance and compliance to a broad spectrum of design and manufacturing constraints. The second aspect is the ability to explore the “deviations” of optimised solutions from the originallyconceived solution. The deviations take into account for both performance-based criteria and the architect's design intent.

Table 15: Values of d1, d2 and CF for the two extreme points A ($d_{i1} \neq 0$, $d_{i2} = 0$) and B ($d_{i1} = 0$, $d_{i2} \neq 0$) of the meta-Pareto front for the three analyses

	Number of cycles					
	150		1500		15000	
	Point A	Point B	Point A	Point B	Point A	Point B
Deviation from proposed design d_{i1}	5.98%	Nil	6.90%	Nil	8.84%	Nil
Deviation from reference point d_{i2}	Nil	402.51 t_{CO_2}	nil	597.67 t_{CO_2}	Nil	776.67 t_{CO_2}
Weighted Constraint Score	2.5	1.5	2.5	1.5	2.5	1.5

A typical usage scenario for the above diagrams would include the selection of the best solutions on the meta-front starting from solutions with the lowest distance from the originally-intended design. Figure 46b shows an example of a design solution that improves the performance of the proposed design while keeping the aesthetical variation from the originally-intended design (Figure 46a) to the minimum (d_1 = 1.86%). The solution in Figure 46b was chosen from the analysis with numOfCycles=15000 (point C in Figure 45c). The different aesthetical appearance of the solution, combined with the variation in the material properties, led to a reduction of 218 t_{CO_2} for the whole façade from the initially-intended design. This is mostly due to the reduction in insulation material and concrete thickness, as well as to the reduced window-to-wall area. However, this solution presents a WCS equal to 2.5, 1 point higher than the original design. This is due to the presence of a design error regarding the absence of a minimum clearance of 20cm on the supporting structural slab (Figure 46c). Therefore, designers either need to find solutions to support the panel with a smaller clearance (e.g. by developing a more engineered solution) or by moving down the meta-front to look for solutions with lower weighted constraint scores (and lower d_2), even if the aesthetical deviation from the proposed design d_1 increases (Figure 45d).

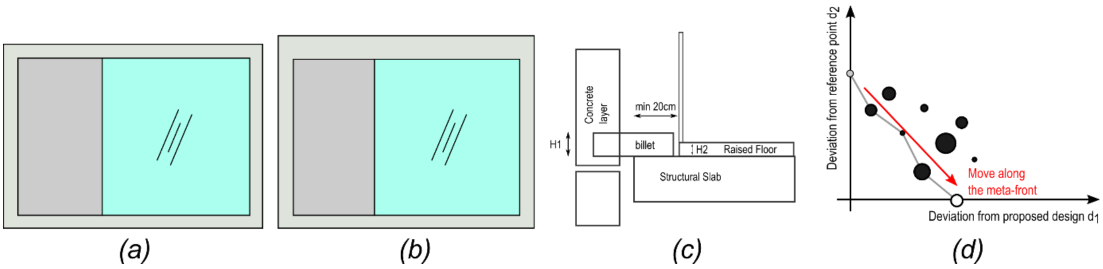


Figure 46: Comparison between (a) the original design (point B in Figure 45c) and (b) the chosen design solution that improves the performance of the original design (point C in Figure 45c). Despite performing better, this solution presents an error in the position of the structural billet, which requires a minimum 20cm clearance on the structural slab (c). A possible option is to move further down-left along the meta-front (d)

6.6 Conclusions

The present chapter has shown an approach that uses downstream knowledge (i.e. manufacturing) in upstream processes (i.e. early stage design) to achieve optimised design solutions. The current state of optimisation in façade design focuses on the use of very specific (namely, GA) techniques applied to few domains of interest (e.g. thermal behaviour). This approach captures only partially the interrelationships underlying the design of the product, as the majority of the effort is dedicated to the optimisation algorithm at the expense of the knowledge capture stage. For this reason, more emphasis should be put in the analysis of the product architecture, and in the collection and formalisation of the available design knowledge, even at the expense of obtaining more approximate values of the objective functions.

The proposed methodology provides a decision-making procedure for choosing between a set of non-dominated solutions characterised by specific performance indices. The methodology creates a “meta-domain” of analysis to find trade-offs between performance and architectural intent, while allowing for maximum compliance to manufacturing, logistic and design constraints. Those constraints are not treated as “hard” and consequently, innovation is still possible by exploring apparently non-compliant solutions. Limitations on the choice of points on the Pareto front are therefore addressed and partially reduced: the meta-front is more selective, more readable and richer than a traditional Pareto front, that does not give insights on the architectural intent and manufacturability/buildability criteria.

A case study of a project in London was used to demonstrate the application of the methodology. The results from this case study show that the methodology yields significant carbon savings (up to 218 t_{CO_2} over a 20-years lifespan).

Chapter 7

Conclusions and future work

7.1 Conclusions

This work has investigated ways of collecting, storing, structuring and digitalising engineering knowledge to support the design of prefabricated façades. The main research question (RQ) and secondary research questions (SRQ) set out at the beginning of this thesis (section 1) have been answered in the subsequent chapters of the thesis and are summarised below.

(SRQ1) *What have other industries produced in terms of digital tools to support design?*

So-called knowledge-based engineering (KBE) applications in the aerospace and shipbuilding industries, and relevant design processes, were first reviewed. The review has shown that such industries share similarities with the construction industry (and, more specifically, the façade sector) in that early-design stages are fundamental to define the specified performance. KBE applications are used to rapidly support designers by incorporating various instances of interdisciplinary design knowledge in a single platform. Flight performance in aerospace, and logistics (i.e. ease of installation and transportation) in shipbuilding are the main aspects that are targeted by KBE applications. KBE applications are also used for optimising details (e.g. design for manufacturability of the airplane's wing structure) towards the end of the design process. In contrast, there is a scarcity of such applications in the construction and façade sectors, current research in the management and subsequent digitisation of engineering knowledge at early-design stages. Absence of efforts of this kind can be at the root of one of the major challenges that the construction sector is facing: the inability to tackle design issues in advance, thus leading to expensive, time consuming corrections in the latter design stages.

(SRQ2) *What methodology should we adopt to develop digital tools to support design?*

The methodology developed in this study aims at streamlining the transition from knowledge expressed in loose, natural language to a more formal and easier-to-digitalise type for the final product model. This approach, despite building upon previous work, aims at being simple and open to implement by façade professionals. A theoretical background on how product architecture and object-oriented programming share similarities has also been provided.

(SRQ3) *What would a proof-of-concept of a digital tool supporting design look like?*

The methodology has been applied to a case study of a prefabricated façade panel manufactured by a specific British company. This has served as a testbed for the proof-of-concept to understand strengths and limitations of the proposed approach. It emerged that, if the façade product is considered holistically as the sum of its physical components and relevant engineering knowledge, it is possible to create a digital "twin" able to swiftly respond to design changes. However, two major limitations have been identified and addressed: the effort required to collect knowledge, and the trade-off between the collected knowledge and its detailed implementation into the digital tool's product model.

(SRQ4) *What are the validation strategies to evaluate the effectiveness of such tools?*

The digital tool has then been validated on both simulated and real-world scenarios. In the first case, a workshop with 5 London-based engineering façade consultancies has shown that participants need a combination of domain knowledge and familiarity with digital technologies to use the tool successfully. This work, despite being unique, has shown a series of limitations, such as limited statistical strength and possible acquiescence bias, that need further investigations in future. In the second case, the author has worked in parallel with professionals from the above-mentioned British company on two real-world projects. Results show that the tool helps increase the number of design options and better understand their expected performance / manufacturability in less time.

(SRQ5) *Can we improve façade design optimisation?*

The final part of the work has focussed on using the digital tool to fully-automate the design of the prefabricated product. The proposed approach aims at addressing two current major weaknesses: the focus on the optimisation algorithm, rather than on the inclusion of many interdisciplinary design criteria, and the absence of ways of incorporating the architectural intent into the problem. The proposed approach introduces a meta-domain of analysis composed of three dimensions: one dealing with the performance to be optimised, one considering the compliance to design and manufacturing constraints, and a final one describing how the architectural intent varies from the initially-intended design. The latter is defined by measuring how every geometrical feature varies from the initial solution and is formulated in a similar way to the concept of variance in statistics. The application of the algorithm to a case study has shown that the approach can lead to significant savings (carbon savings in this instance), while limiting the interference with the architect's intent.

(RQ) *Can early-stage façade design be supported with digital tools that integrate multiple design & construction criteria?*

This work has developed and validated a proof-of-concept (estimated technology readiness level: TRL 6) and thereby has shown that it is possible to support façade design with design and manufacturing knowledge-rich digital tools. This requires the adoption of a methodology that iterates through steps of knowledge collection, structuring in a knowledge-base, and preparation for and implementation in the final digital tool. When developing the tool, it is possible to achieve different levels of detail and insightfulness of the implemented knowledge. The more detailed the knowledge is, the more limited the scope, and therefore the less generic and applicable the tool will be. Conversely, the broader and less detailed the knowledge, the wider the applicability will be.

Product models, by automatic routine calculations, also make façades products less of an engineer-to-order type (ETO, Figure 4), as part of the engineering design is not a concern for the designer anymore. Thus, PM shift the product towards (but without reaching) a fully-designed one, thus making it more akin to a make-to-order type (MTO). Figure 47 extends Figure 4 by adding a new product type: product supported by a digital configuration tool (e.g. knowledge-based engineering application). These products have yet to be designed but they are represented by a PM that "knows" how to design them. They lie in between ETO types, which require full engineering design to be repeated on every client order, and MTO types, which instead have already been designed and only need to be manufactured as the order is placed.

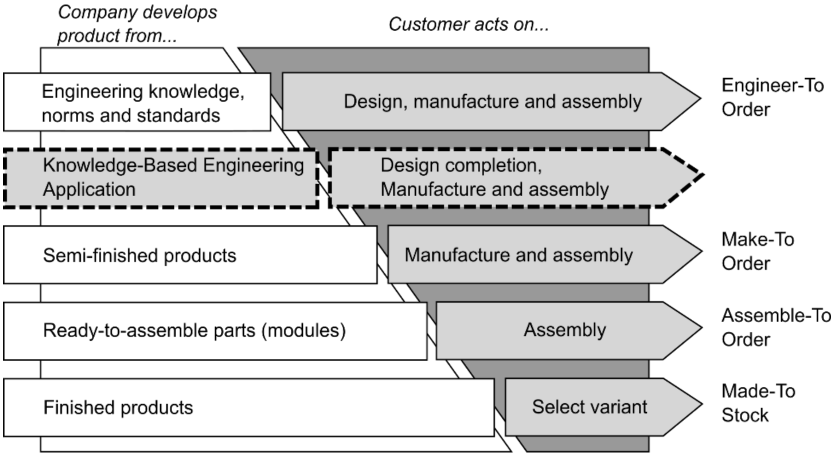


Figure 47: Extended version of Figure 4 with products that are already partially designed, thus making them more similar to make-to-order products

The digitisation of engineering knowledge therefore has the potential to increase the level of awareness and reduce design times during the early stages of design. This has, in turn, favourable effects on the future manufacturability and installation of the façade product, which will be easier to manufacture and that will be more likely to respond to the initially-specified performance. In this work, this potential has been explored and strengths and challenges have been identified, by applying a digital tool to real-world scenarios. Future work is needed to completely exploit this potential fully.

7.2 Future work

The present work, while endeavouring to provide the answers to the research questions, has highlighted possible new research strands that were not fully explored during this three-year research program.

7.2.1 DFD: design for digitalisation

In this work, a pre-specified façade typology was used as a case study for the research. The product in question was a non load-bearing, precast concrete panel, whose product architecture is so to satisfy a series of performance- and manufacturing-based criteria. Thus, the product was conceived to be designed for performance (DFP) and for manufacturing (DFM). However, the implementation into the PM poses a series of additional challenges, which fall under the realm of computer science. So, what if, when developing a novel façade product, one would conceive it so that it is easy to be digitalised? This would require the PM implementation to be treated the same way as fire, acoustic, and thermal requirements, i.e. that ease of PM implementation would be an additional façade performance requirement.

7.2.2 Standardised procedures for testing digital tools

The digitalisation into a configurable PM requires the tool to be fully usable by the prospective users. Although the present research has introduced a methodology for testing the usability of the tool, a series of limitations have been addressed. Future work requires more robust methodologies.

7.2.3 Bayesian Machine Learning for small datasets

Equation 1 determined the thickness of the concrete layer of the precast concrete panel via a multi-linear regression based on a small set of past cases. Those cases correlated the thickness with the main features of the façade panel, such as height or window-to-wall-ratio, to the concrete thickness. However, if additional cases are added, the model's linearity might be lost (e.g. quadratic), thus requiring the user to manually modify and validate the new model. Conversely, so-called model-free techniques do not require an a-priori knowledge of the underlying function. An example is Gaussian Processes, that build upon Bayesian statistics, where some prior knowledge of the phenomenon (i.e. prior belief) is updated by actual data. This approach is particularly useful whenever the dataset is small – as in the AEC sector, where the number of cases is in the order of tens, hundreds or, more rarely, few thousands. Implementation of this type would be preferred to the simple multi-linear regression and studied further.

References

[1] Construction Industry Council. Offsite Housing Review 2013:1–43.

[2] McKinsey & Company. The construction productivity imperative 2015. www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/the-construction-productivity-imperative.

[3] Eekhout M. Methodology for Product Development in Architecture. IOS Press; 2009.

[4] Hansen BL. Development of Industrial Variant Specification Systems. Doctoral Dissertation, Technical University of Denmark, 2003.

[5] Rudberg M, Wikner J. Mass customization in terms of the customer order decoupling point. Production Planning & Control 2004;15:445–58. doi:10.1080/0953728042000238764.

[6] Eurostat. Greenhouse gas emissions by industries and households 2016. http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emissions_by_industries_and_households.

[7] Chandrasegaran SK., Ramani K. b, Sriram RD., Horváth I., Bernard A., Harik RF., et al. The evolution, challenges, and future of knowledge representation in product design systems. CAD Computer Aided Design 2013;45:204–28. doi:10.1016/j.cad.2012.08.006.

[8] Kassem M, Mitchell D. Bridging the gap between selection decisions of façade systems at the early design phase: Issues, challenges and solutions. Journal of façade Design and Engineering 2015;3:165–83. doi:10.3233/FDE-150037.

[9] Voss E, Jin Q, Overend M. A BPMN-Based Process Map for the Design and Construction of Façades. Journal of façade Design and Engineering 2013;1:17–29. doi:10.3233/FDE-130006.

[10] RIBA. RIBA Plan of Work 2013 - Designing for Manufacture and Assembly. 2013.

[11] Henriksen T, Lo S, Knaack U. The impact of a new mould system as part of a novel manufacturing process for complex geometry thin-walled GFRC. Architectural Engineering and Design Management 2016;12:231–49. doi:10.1080/17452007.2016.1159540.

[12] Voss E, Overend M. A Tool that Combines Building Information Modeling and Knowledge Based Engineering to Assess Façade Manufacturability. Advanced Building Skins, Gratz: 2012.

[13] Karsai P. Façade procurement: The Role of the Façade Consultant.

International Conference on Building Envelope Systems and Technology, 1997.

[14] Vaz D, Al Bizri S, Gray C. The Management of the Design of Modern Curtain Wall Cladding Systems. ARCOM 24th Annual Conference, 2008, p. 759–68.

[15] RIBA. RIBA Plan of Work 2013 Overview 2013. https://www.ribaplanofwork.com/Download.aspx.

[16] Eastman C, Sacks R, Panushev I, Aram V, Yagmur E. Information Delivery Manual for Precast Concrete. PCI-Charles Pankow Foundation: 2009.

[17] Miles BL, Swift K. Design for Manufacture and Assembly. Manufacturing Engineer 1998:221–4.

[18] Namouz E, Summers JD, Mocko GM. Reasoning: Source of Variability in the Boothroyd and Dewhurst Assembly Time Estimation Method. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2012. doi:10.1115/detc2012-71075.

[19] Rehman S, Guenov MD. A Methodology for Modelling Manufacturing Costs at Conceptual Design. Computers & Industrial Engineering 1998;35:623–6. doi:10.1016/S0360-8352(98)00174-0.

[20] Asiedu Y, Gu P. Product Life Cycle Cost Analysis: State of the Art Review. International Journal of Production Research 1998;36:883–908. doi:10.1080/002075498193444.

[21] Stokes M. Managing Engineering Knowledge – MOKA: Methodology for Knowledge Based Engineering Applications. American Society of Mechanical Engineers; 2001.

[22] Baxter D, Gao J, Case K, Harding J, Young R, Cochrane S, et al. An engineering design knowledge reuse methodology using process modelling. Research in Engineering Design 2007;18:37–48. doi:10.1007/s00163-007-0028-8.

[23] Voss E. An Approach to Support the Development of Manufacturable Façade Designs. Doctoral dissertation, University of Cambridge, 2013.

[24] Knowledge Transfer Network. High Value Manufacturing - Modelling and Simulation Best Practice (SimBest) - Best Practice Final Report 2016.

[25] Jin Q, Overend M. A prototype whole-life value optimization tool for façade design. Journal of Building Performance Simulation 2013;1493. doi:10.1080/19401493.2013.812145.

[26] Jacomy M, Venturini T, Heymann S, Bastian M. ForceAtlas2, a continuous graph layout algorithm for handy network visualization designed for the Gephi software. PLoS ONE 2014;9. doi:10.1371/journal.pone.0098679.

[27] Glass and façade Technology (gFT) Research Group. façade design tools - force-directed layout 2016. http://www.gft.eng.cam.ac.uk/resources/façade-design-tools-force-directed-layout (accessed July 11, 2017).

[28] BPMN 2017. http://www.bpmn.org/.

[29] Willner O, Gosling J, Schönsleben P. Establishing a maturity model for design automation in sales-delivery processes of ETO products. Computers in Industry 2016;82:57–68. doi:10.1016/j.compind.2016.05.003.

[30] Bronsart R, Wiegand G, Koch T. A Collaborative Platform for Ship Design. 12th International Conference on Computer Applications in Shipbuilding (ICCAS), 2005, p. 1–15.

[31] Bronsart R, Gau S, Luckau D, Sucharowski W. Enabling Distributed Ship Design and Production Processes by an Information Integration Platform. 12th International Conference on Computer Applications in Shipbuilding (ICCAS) 2005:23–6.

[32] Caracchi S, Sriram PK, Semini M, Strandhagen JO. Capability Maturity Model Integrated for Ship Design and Construction. IFIP International Conference on Advances in Production Management Systems, Springer, Berlin, Heidelberg.: 2014, p. 296–303.

[33] Semini M, Haartveit DEG, Alfnes E, Arica E, Brett PO, Strandhagen JO. Strategies for Customized Shipbuilding with Different Customer Order Decoupling Points. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment 2014;228:362–72. doi:10.1177/1475090213493770.

[34] Pero M, Stößlein M, Cigolini R. Linking Product Modularity to Supply Chain Integration in the Construction and Shipbuilding Industries. International Journal of Production Economics 2015:1–14. doi:10.1016/j.ijpe.2015.05.011.

[35] Solesvik MZ. A Collaborative Design in Shipbuilding: Two Case Studies. IEEE International Conference on Industrial Informatics (INDIN) 2007;1:299–304. doi:10.1109/INDIN.2007.4384773.

[36] Tann W, Shaw HJ. The Collaboration Modelling Framework for Ship Structural Design. Ocean Engineering 2007;34:917–29. doi:10.1016/j.oceaneng.2006.05.012.

[37] U.S. Department of Commerce. Product Breakdown Structure Maritime Administration Todd Pacific Shipyards Corporation. 1980.

[38] Nicolai LM, Carichner GE. Fundamentals of Aircraft and Airship Design, Volume I - Aircraft Design. Reston, VA: AIAA Education Series; 2010. doi:10.2514/4.867538.

[39] Curran R. Integrating Aircraft Cost Modeling into Conceptual Design.

Concurrent Engineering 2005;13:321–30. doi:10.1177/1063293X05060698.

[40] Anderson J. Aircraft Performance and Design. 1st ed. Boston: WCB/McGraw-Hill; 1999.

[41] Boothroyd G, Dewhurst P, Knight W. Product Design for Manufacture and Assembly. 3rd ed. CRC Press; 2010.

[42] Verhagen WJC, Bermell-Garcia P, Van Dijk REC, Curran R. A Critical Review of Knowledge-Based Engineering: An Identification of Research Challenges. Advanced Engineering Informatics 2012;26:5–15. doi:10.1016/j.aei.2011.06.004.

[43] Reddy EJ, Sridhar CN V, Rangadu VP. Knowledge Based Engineering : Notion , Approaches and Future Trends. American Journal of Intelligent Systems 2015;5:1–17. doi:10.5923/j.ajis.20150501.01.

[44] La Rocca G. Knowledge Based Engineering: Between AI and CAD. Review of a Language Based Technology to Support Engineering Design. Advanced Engineering Informatics 2012;26:159–79. doi:10.1016/j.aei.2012.02.002.

[45] Uschold M, Gruninger M. Ontologies: Principles , Methods and Applications. Knowledge Engineering Review 1996;11:69. doi:10.1017/s0269888900007797.

[46] Sandberg M. Knowledge Based Engineering: in Product Development. Luleå Tekniska Universitet: 2003.

[47] Cooper S, Fan I, Li G. Achieving competitive advantage through knowledge-based engineering: a best practice guide. Prepared for the Dept. of Trade and Industry by Dept. of Enterprise Integration: Cranfield University; 1999.

[48] Van Der Laan AH, Van Tooren MJL. Parametric Modeling of Movables for Structural Analysis. Journal of Aircraft 2005;42:1605–13. doi:10.2514/1.9764.

[49] Kulon J, Mynors DJ, Broomhead P. A Knowledge-Based Engineering Design Tool for Metal Forging. Journal of Materials Processing Technology 2006;177:331–5. doi:10.1016/j.jmatprotec.2006.04.062.

[50] Chapman CB, Pinfold M. The Application of a Knowledge-Based Engineering Approach to the Rapid Design and Analysis of an Automotive Structure. Advances in Engineering Software 2001;32:903–12. doi:10.1016/S0965-9978(01)00041-2.

[51] Verhagen WJC. An Ontology-Based Approach for Knowledge Lifecycle Management within Aircraft Lifecycle Phases. Doctoral dissertation, Delft University, 2013.

[52] Verhagen WJC, Curran R. Knowledge-Based Engineering Review: Conceptual Foundations and Research Issues. New World Situation: New

Directions in Concurrent Engineering, Springer; 2010.

[53] Preston S, Chapman C, Pinfold M, Smith G. Knowledge Acquisition for Knowledge-Based Engineering Systems. International Journal of Information Technology and Management 2005;4:1. doi:10.1504/IJITM.2005.006401.

[54] Curran R, Verhagen WJC, van Tooren MJL, van der Laan TH. A Multidisciplinary Implementation Methodology for Knowledge Based Engineering: KNOMAD. Expert Systems with Applications 2010;37:7336–50. doi:10.1016/j.eswa.2010.04.027.

[55] Lohith M, Prasanna L, Vaderahobli DH. Translating MOKA Based Knowledge Models into a Generative CAD Model in CATIA V5 Using Knowledgeware. International Conference on Modeling, Simulation and Visualization Methods(MSV) The Steering Committee of The World Congress in Computer Science, Computer Engineering and Applied Computing (WorldComp) 2013.

[56] Chapman C, Preston S, Pinfold M, Smith G. Utilising Enterprise Knowledge with Knowledge-Based Engineering. International Journal of Computer Applications in Technology 2007;28:169–79. doi:10.1504/IJCAT.2007.013354.

[57] La Rocca G, Van Tooren MJL. Enabling Distributed Multi-Disciplinary Design of Complex Products: a Knowledge Based Engineering Approach. Journal of Design Research 2007;5:333–52. doi:10.1504/JDR.2007.014880.

[58] Bermell-Garcia P, Verhagen WJC, Astwood S, Krishnamurthy K, Johnson JL, Ruiz D, et al. A framework for management of Knowledge-Based Engineering applications as software services: Enabling personalization and codification. Advanced Engineering Informatics 2012;26:219–30. doi:10.1016/j.aei.2012.01.006.

[59] Wu YH, Shaw HJ. Document Based Knowledge Base Engineering Method for Ship Basic Design. Ocean Engineering 2011;38:1508–21. doi:10.1016/j.oceaneng.2011.07.014.

[60] Elgh F, Cederfeldt M. Concurrent Cost Estimation as a Tool for Enhanced Producibility-System Development and Applicability for Producibility Studies. International Journal of Production Economics 2007;109:12–26. doi:10.1016/j.ijpe.2006.11.007.

[61] Yang HZ, Chen JF, Ma N, Wang DY. Implementation of Knowledge-Based Engineering Methodology in Ship Structural Design. CAD Computer Aided Design 2012;44:196–202. doi:10.1016/j.cad.2011.06.012.

[62] Cui J, Wang D, Shi Q. Structural Topology Design of Container Ship Based on Knowledge-Based Engineering and Level Set Method. China Ocean Engineering 2015;29:551–64. doi:10.1007/s13344-015-0038-7.

[63] Stueber TJ, Le DK, Vrnak DR. Hypersonic Vehicle Propulsion System Control Model Development Roadmap and Activities. 2009.

[64] Feng H, Luo M, Liu H, Wu Z. A Knowledge-Based and Extensible Aircraft Conceptual Design Environment. Chinese Journal of Aeronautics 2011;24:709–19. doi:10.1016/S1000-9361(11)60083-6.

[65] Choi JW. Architecture of a Knowledge Based Engineering System for Weight and Cost Estimation for a Composite Airplane Structures. Expert Systems with Applications 2009;36:10828–36. doi:10.1016/j.eswa.2008.10.049.

[66] Emberey CL, Milton NR, Berends JPTJ, Tooren MJL Van, Elst SWG Van Der, Vermeulen B. Application of Knowledge Engineering Methodologies to Support Engineering Design Application Development in Aerospace. 7th AIAA Aviation Technology, Integration and Operations Conference (ATIO), 2007, p. 18–20. doi:10.2514/6.2007-7708.

[67] Corallo A, Margherita A, Pascali G, Turrisi G. Streamlining New Product Development in Aerospace Through Knowledge Based Engineering. 21th Annual Conference of the Production and Operations Management Society, Vancouver: 2010, p. 1–21.

[68] Gross MD. Why Can't CAD Be More Like Lego? CKB, a Program for Building Construction Kits. Automation in Construction 1996;5:285–300. doi:10.1016/S0926-5805(96)00154-9.

[69] Ganeshan R, Stumpf A, Chin S, Liu L, Harrison B. Integrating Object-Oriented CAD and Rule-Based Technologies. US Army Construction Engineering Research Laboratory, Champaign (IL), United States: 1996.

[70] Sandberg M, Johnsson H, Larsson T. Knowledge-Based Engineering in Construction: The Prefabricated Timber Housing Case. Electronic Journal of Information Technology in Construction 2008;13:408–20.

[71] Aram S, Eastman C, Sacks R. A Knowledge-Based Framework for Quantity Takeoff and Cost Estimation in the AEC Industry Using BIM. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction. Vol. 31., Vilnius Gediminas Technical University, Department of Construction Economics & Property: 2014, p. 1.

[72] Karhu V. product model Based Design of Precast façades. Electronic Journal of Information Technology in Construction 1997;2.

[73] Said HM, Chalasani T, Logan S. Exterior prefabricated panelized walls platform optimization. Automation in Construction 2017;76:1–13. doi:10.1016/j.autcon.2017.01.002.

[74] Fuchs A, Peters S, Hans O, Möhring J. Schüco Parametric System - Uniqueness in Series. Advanced Building Skins, Graatz: 2015.

[75] Zahner. ShopFloor 2016. http://www.shopfloorapp.com/.

[76] Isaac S, Bock T, Stoliar Y. A methodology for the optimal modularization of building design. Automation in Construction 2016;65:116–24. doi:10.1016/j.autcon.2015.12.017.

[77] Zhong RY, Peng Y, Xue F, Fang J, Zou W, Luo H, et al. Prefabricated construction enabled by the Internet-of-Things. Automation in Construction 2017;76:59–70. doi:10.1016/j.autcon.2017.01.006.

[78] Nath T, Attarzadeh M, Tiong RLK, Chidambaram C, Yu Z. Productivity improvement of precast shop drawings generation through BIM-based process re-engineering. Automation in Construction 2015;54:54–68. doi:10.1016/j.autcon.2015.03.014.

[79] Eastman C, Lee JM, Jeong YS, Lee JK. Automatic Rule-Based Checking of Building Designs. Automation in Construction 2009;18:1011–33. doi:10.1016/j.autcon.2009.07.002.

[80] Aram S. A Knowledge-Based System Framework For Semantic Enrichment And Automated Detailed Design In The Aec Projects. Doctoral dissertation, Georgia Institute of Technology, 2015.

[81] Belsky M, Sacks R, Brilakis I. Semantic Enrichment for Building Information Modeling. Computer-Aided Civil and Infrastructure Engineering 2015;31:261–74. doi:10.1111/mice.12128.

[82] Ulrich K. The Role of Product Architecture in the Manufacturing Firm. Research Policy 1995;24:419–40. doi:10.1016/0048-7333(94)00775-3.

[83] Suh NP. The principles of design. Oxford Series on Advanced Manufacturing ; 6 1990;6:xiv, 401p.

[84] Klein T. Integral Façade Construction - Towards a New Product Architecture for Curtain Walls. 2013.

[85] Milton NR. Knowledge Acquisition in Practice: A Step-by-step Guide. 1st ed. Springer-Verlag London; 2007. doi:10.1007/978-1-84628-861-6.

[86] OMG. UML 2016. http://www.uml.org/.

[87] Author's webpage 2016. http://www2.eng.cam.ac.uk/~jm2026/jm_web/ResearchWork/kbe-tool-use-cases/index.html.

[88] Obinger M, Bernardinis R, Cieplik W, Vollert H-J, Weckenmann H. Precast Factory Explore Manufacturing , Laing O'Rourke (Part 1/2). Concrete Plant International 2010:158–70.

[89] Bostock M, Ogievetsky V, Heer J. D3 : Data-Driven Documents. In: IEEE, editor. IEEE Transactions on Visualization & Computer Graphics, 2011, p. 2301–9. doi:10.1109/TVCG.2011.185.

[90] Holten D. Hierrchical Edge Bundles: Visualizaiton of Adjacency Relations in Hierarchical Data. IEEE Transactions on Visualization and Computer

Graphics 2006;12:741–8. doi:10.1109/TVCG.2006.147.

[91] Montali J, Overend M, Pelken PM, Sauchelli M. Knowledge-Based Engineering Applications for Supporting the Design of Precast Concrete Façade Panels. ICED17: International Conference of Engineering Design, Vancouver: 2017.

[92] Cavalieri S, P.Maccarrone, R.Pinto. Parametric vs. neural network models for the estimation of production costs: A case study in the automotive industry. International Journal of Production Economics 2004;91:165–77. doi:10.1016/j.ijpe.2003.08.005.

[93] Chu X, Holm H. Product manufacturability control for concurrent engineering. Computers in Industry 1994;24:29–38. doi:10.1016/0166-3615(94)90006-X.

[94] Eastman C. BIM handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors. 2. ed. Hoboken, NJ Wiley; 2011.

[95] Goicoechea A, Hansen DR, Duckstein L. Multiobjective Decision Analysis with Engineering and Business Applications. 1982.

[96] Ashby MF. Multiple Constraints and Conflicting Objectives. Materials Selection in Mechanical Desing. 4th ed., Elsevier; 2011, p. 197–216. doi:10.1016/B978-1-85617-663-7.00008-4.

[97] Hensen JLM, Lamberts R. Building Performance Simulation for Design and Operation 2011:xxiv, 507 p.

[98] Hall IJ, Prairie RR, Anderson HE, Boes EC. Generation of a Typical Meteorological Year, 1978.

[99] Jin Q. Towards a Whole-life Value Optimisation Model for façade Design. 2013.

[100] gFT Research Group. Resources 2015. http://www.gft.eng.cam.ac.uk/resources.

[101] Montali J, Overend M, Pelken PM, Sauchelli M. Towards façades as Make-To-Order products--the role of Knowledge-Based-Engineering to support design. Journal of façade Design and Engineering 2017;5:101–12. doi:http://dx.doi.org/10.7480/jfde.2017.2.1744.

[102] Hammond GP, Jones CI. Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers - Energy 2008. doi:10.1680/ener.2008.161.2.87.

[103] ANSI/ASHRAE/IES Standard 90.1-2016. Energy Standard for Buildings Except Low-Rise Residential Buildings 2016.

[104] Masood T, Roy R, Harrison A, Xu Y, Gregson S, Reeve C. Integrating through-life engineering service knowledge with product design and

manufacture. International Journal of Computer Integrated Manufacturing 2015;28:59–74. doi:10.1080/0951192X.2014.900858.

[105] Fox S, Marsh L, Cockerham G, Fox S, Marsh L, Constructability GC, et al. Constructability rules : guidelines for successful application to bespoke buildings Constructability rules : guidelines for successful application to bespoke buildings 2010;6193. doi:10.1080/01446190210163606.

[106] Yuan Z, Sun C, Wang Y. Automation in Construction Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. Automation in Construction 2018;88:13–22. doi:10.1016/j.autcon.2017.12.021.

[107] Kim M, Mcgovern S, Belsky M, Middleton C. A suitability analysis of precast components for standardized bridge construction in the United Kingdom. Procedia Engineering 2016;164:188–95. doi:10.1016/j.proeng.2016.11.609.

[108] Gerth R, Boqvist A, Bjelkemyr M, Lindberg B, Gerth R, Boqvist A, et al. Design for construction : utilizing production experiences in development 2013;6193. doi:10.1080/01446193.2012.756142.

[109] Bralla. Design for Manufacturability Handbook 1998.

[110] Best Manufacturing Practices and Centre of Excellence. Producibility System Guidelines for Successful Companies: The Five Steps to Success. College Park: 1999.

[111] Keane R, Fireman H. Producibility in the Naval Ship Design Process : A Progress Report 1992.

[112] Bruce GJ. Business of shipbuilding. London: LLP; 1999.

[113] Chryssolouri G. Manufacturing Systems: Theory and Practice. 2nd ed. New York: Springer Science + Business Media; 2006.

[114] Sanders A, Belie G, Allen J, Pollari G, Fischer K, Stirk C, et al. Modeling & Simulation Investment Needs for Producible Designs and Affordable Manufacturing Systems Engineering Implications. National Defense Industry Association (NDIA) Joint Committee for Systems Engineering and Manufacturing (JCSEM) M&S Subcommittee Final Report 2010.

[115] OSD Manufacturing Technology Program. Manufacturing Readiness Level (MRL) Deskbook 2011.

[116] Vallhagen J, Madrid J, Söderberg R, Wärmefjord K. An Approach for Producibility and DFM-Methodology in Aerospace Engine Component Development. Procedia CIRP 2013;11:151–6. doi:10.1016/j.procir.2013.07.035.

[117] Elgh F. Supporting Management and Maintenance of Manufacturing Knowledge in Design Automation Systems. Advanced Engineering Informatics 2008;22:445–56. doi:10.1016/j.aei.2008.05.004.

Appendix A: Data, information and knowledge (and wisdom)

The concepts of data, information and knowledge have been used extensively in the recent years, mainly due to the rise in web-based technologies. These three concepts constitute the basic vocabulary in many domains, such as knowledge management (KM), Ontology Engineering and Computer Science. Data, information and knowledge are normally represented by a triangle (Figure 48), with the lower levels providing the basis for the above concepts.

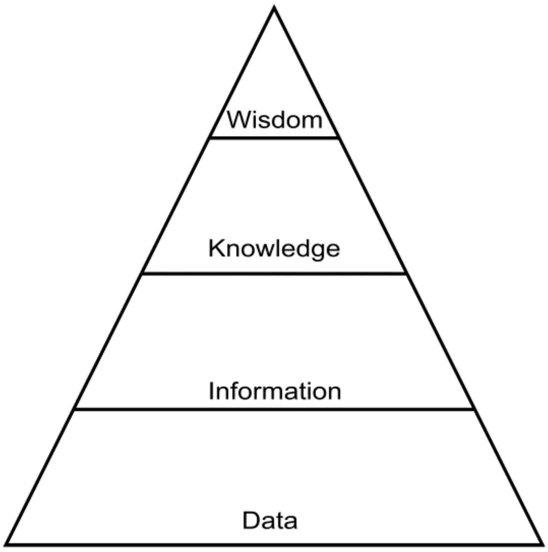


Figure 48: Relationship between data, information, knowledge and wisdom

The word "data" is the plural version of the Latin word *datum*, which means "given". In English, it can be equally used as a singular or a plural noun. A piece of data is therefore any signal, element or form of representation of a specific phenomenon. Its essential characteristic is therefore the capability to be perceived by us regardless of its context; data can be any vibration, character or letter, or impulse of energy. Very often the word "data" is preceded by the adjective "raw", to signify the nature of data as entities that exist without being manipulated or contextualised. In façade design and in other domains, data can be a number, or the digits constituting that number, regardless of its real meaning (e.g.: the value of the solar transmittance of a glass).

Information (from the Latin verb *informare*, to give shape) is commonly known as data in a context. Information leads to a higher level of understanding of data, which now acquires meaning due to its context. A number therefore produces information when associated with the domain it is referring to. As in the above example, if the solar trasmittance of a specific glass is 0.65, this is information since one can be *informed* about the specific solar properties of a certain glass.

Knowledge is the ability to use information in a proactive and creative way. Knowledge is "*actionable understanding*" [104], based on some contextualised data (aka information). As stated by Milton [85], "*knowledge is an active thing that manipulates, transforms or creates something out of something else*". Knowledge can be in turn subdivided into explicit versus tacit, or conceptual versus procedural [85]. Explicit knowledge can be directly written or communicated, whereas implicit (also called heuristic) knowledge lies within the person holding it and it is very often acquired by experience. Implicit knowledge is regarded as the most precious form of knowledge and very often it is implemented (i.e. made explicit) into one or more IF…THEN… rules to make it usable by others. Conceptual knowledge mostly concerns the state of things and their properties; procedural knowledge describes processes and instructions about how to perform specific tasks.

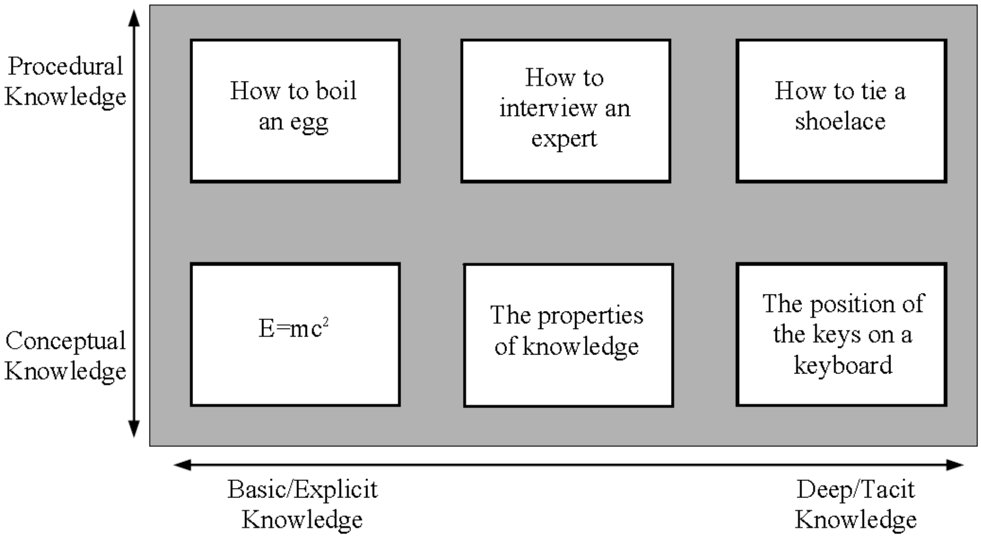


Figure 49: Examples of different forms of knowledge [85]

The last stage of the pyramid in Figure 48 is wisdom. Wisdom consists of the ability to foresee consequences of a specific action, based on some precedent knowledge. It therefore includes ethical aspects such as the ability to distinguish between good and bad.

Appendix B: Design for manufacture and assembly (DFMA)

Design for manufacture and assembly (DFMA) is the combination of design for manufacture (DFM) and design for assembly (DFA). Using the words of Boothroyd, Dewhurst and Knight [41], these two approached refer to "*the design for the ease of manufacture of the collection of parts that form the product after assembly*" and "*the design of the product for the ease of assembly*", respectively.

DFMA is used for understanding the cost (either monetary or required time) arising from a specific design choice. It also includes constraints (e.g.: dimensions, weight) associated with specific manufacturing/assembly processes. It was developed in the early '70s by Geoff Boothroyd in a handbook for machining small parts. It then become a book now in its third edition [41]. The approach covers a whole spectrum of manufacturing and assembly processes, from design for machining or injection moulding, to design for manual or robot assembly. It normally consists of general guidelines, e.g. on how to design parts for ease in handling and assembly, and of empirical, semi-empirical or analytical relations about time or cost of specific manufacturing processes (e.g.: milling).

The construction sector is showing a growing interest in the DFMA approach and to extend Boothroyd et al.'s work to construction-specific tasks, especially for prefabricated components. The Royal Institution of British Architects (RIBA) [10] has produced a guideline that specifies what DFMA-related criteria should be followed at each design & construction stage. Similarly, Fox et al. [105] developed constructability rules based on DFMA principles to be applied at each design stages. Yuan et al. [106] define a specific design process in which a "DFMA-oriented architectural design team", formed of architects, structural engineers and contractor-side designers works collaboratively to build the BIM files of prefabricated elements in Autodesk Revit. Kim et al. [107] produced an analysis of both general and product-specific DFMA criteria for standardising the production of prefabricated bridges in the UK. Gerth et al. [108] define “Design for Construction” an approach that uses experience on past project to develop best DFMA-related practices to be fed upstream in the design process.

Appendix C: List of investigated tools

Name	Geometry manipulation	Design Stage	Design aspect	Product-Specific?
Revit	3D	All stages	Architectural design / BIM / shop drawing	Yes
Allplan	3D	All stages	Architectural design / BIM / shop drawing	Yes
Catia	3D	Technical / Construction	Shop drawing / Manufacturability / BIM	Yes
Solidworks	3D	Technical / Construction	Shop drawing / Manufacturability / BIM	Yes
Inventor	3D	Technical / Construction	Shop drawing / Manufacturability / BIM	Yes
Sketchup	3D	Concept / Developed	Architectural design	Yes
Rhinoceros	3D	Concept / Developed	Architectural design	No
Dynamo	3D	Concept / Developed	Architectural design	No
Green Building Studio	3D	All stages	Energy / Daylight	No
IES VE	3D	All stages	Energy / Daylight / Comfort	No
Flixo	2D	Technical / Construction	Thermal	No
SchuCal	No geometry	Technical / Construction	Order placement / Cost / Thermal / Structural / manufacturability / Shop Drawing	Yes
Ecotect	3D	All stages	Energy / Daylight / Comfort	No
Energy Plus	No geometry	All stages	Energy / Daylight / Comfort	No
gFT Optimisation tool	No geometry	Concept / Developed	Energy / Daylight / Comfort	No
COMFEN	3D	Concept / Developed	Energy / Daylight / Comfort	No
WIC3D	3D	Concept / Developed	Architectural design	Yes
WIS	No geometry	Technical / Construction	Thermal / visual	Yes
Window	No geometry	Technical / Construction	Thermal / visual	Yes
Therm	2D	Technical / Construction	Thermal	No
Calumen II	No geometry	Technical / Construction	Thermal / visual	Yes
Ucal	No geometry	Concept / Developed	Thermal	Yes
Design Builder	3D	All stages	Energy / Daylight / Comfort	No
TechSketch	3D	Concept / Developed	Architectural design	Yes
MEPLA	No geometry / 3D	Technical / Construction	Structural	No
WinSLT	No geometry	Technical / Construction	Thermal / visual	Yes
WinIso2D	2D	Technical / Construction	Thermal	No
WinIso3D	3D	Technical / Construction	Thermal	No
GlasGlobal	No geometry	Technical / Construction	Structural	No
Trisco / Solido	3D	Technical / Construction	Thermal	No
Bisco / Kobru86	2D	Technical / Construction	Thermal	No
Glastik	No geometry	Technical / Construction	Structual	No
Halfen Dimensioning Software	No geometry	Technical / Construction	Structual	Yes
Tilt-up concrete wall panels	No geometry	Technical / Construction	Structual	No
Advanced Concrete	3D	Technical / Construction	Shop drawing	No
PanelPlus	2D	Technical / Construction	Structural / Shop drawing	No
Logikal	2D	Technical / Construction	Cost / Thermal / Structural / Manufacturability / Shop drawings	Yes
Glass Performance Analysis	3D	Technical / Construction	Structural	No

LEAP VERTEX	No geometry	Technical / Construction	Structural	No
Tekla	3D	Technical / Construction	Shop drawing / Manufacturability / BIM	Yes
LECWall	No geometry	Technical / Construction	Structural	No
VisualARQ	3D	All stages	Architectural design / BIM	Yes
FenestraPro	3D	Concept / Developed	Energy / Dayligt	No
DIVA	3D	All stages	Energy / Daylight / Comfort	No
KingKong	3D	Concept / Developed	Architectural design	No
SteniSystemSolution	3D	Concept / Developed	Architectural design	Yes
Parametric system	3D	Concept / Developed	Architectural design / Manufacturability / Structural	Yes
SchuCad	2D / 3D	Technical / Construction	Shop drawing	Yes
Open Studio	3D	All stages	Energy / Daylight / Comfort	No
RF-Glass	3D	Technical / Construction	Structural	No
Façade design tool	No geometry	Concept / Developed	Energy	No
GIMA Façade configurator	No geometry	Concept / Developed	Architectural design	Yes
CloudWall	3D	Technical / Construction	Architectural design / Cost / Order placement	Yes
DTS glazing designer	No geometry	Concept / Developed	Energy	No
AGC glass configurator	No geometry	Technical / Construction	Thermal / visual	Yes
Preliminary structural analysis	No geometry	Concept / Developed	Structural	Yes
U-wert	No geometry	Technical / Construction	Thermal	Yes
Design Palette visualiser	No geometry	Concept / Developed	Architectural design	Yes
Construct IGU	No geometry	Technical / Construction	Thermal / visual	Yes
ISOGON Window Configurator	No geometry	Technical / Construction	Order placement	Yes
Thermix Window Configurator	No geometry	Concept / Developed	Architectural design	Yes
VELUX roof window price calculator	No geometry	Technical / Construction	Cost / Order placement	Yes
U-value calculator	No geometry	Concept / Developed	Thermal	Yes
Optima IWI System Calculator	No geometry	Technical / Construction	Architectural design / Cost / Order placement	Yes
Pilkington spectrum	No geometry	Technical / Construction	Thermal / visual	Yes

Appendix D: Detailed features of the digital tool

The platform within which the digital tool is built is Rhinoceros 5 (Figure 50, left), a 3D modeller software widely used amongst designers for early-stage architectural design. Rhinoceros contains a plugin named Grasshopper (GH - Figure 50, right) to generate primitive geometries whose main features are controlled parametrically. Grasshopper presents a series of so-called "components", either representing elementary geometries or transformations over the elementary geometries. Normally, components take one or more input values on the left side and give one or more output values on the right side. Components are linked to each other to form a network called "definition". Definitions give rise to more complex 3D parametric models that are then visualised in the Rhinoceros environment.

The created digital tool is a definition of a mixture of standard and custom-built components, created via Visual Studio and implemented in C#. Figure 50 shows the basic definition (right) and the digital model as visualised in Rhinoceros (left). There are three custom components representing: the panel as a whole, the primary structure and the opening. The geometry of these three physical entities is controlled by so-called sliders, a standard GH component that changes the value of a number between a user-specified interval. Sliders are used to change parametrically, for instance, the length of the panel shown in Figure 50.

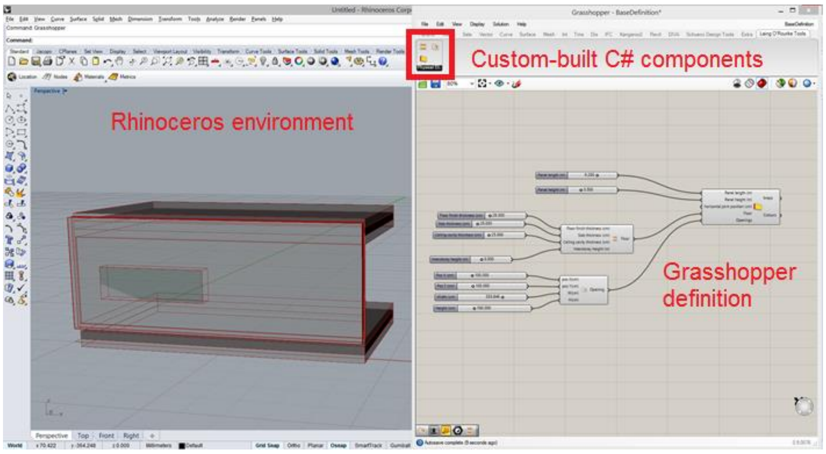
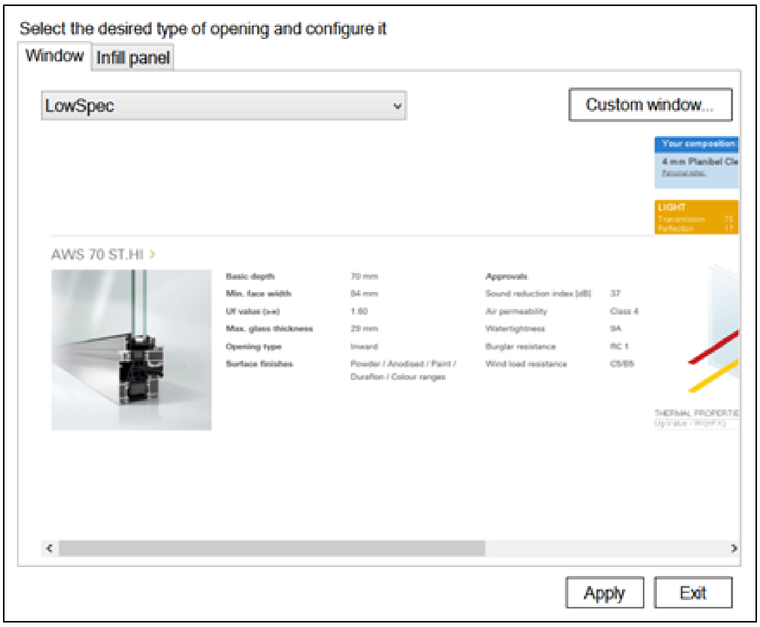


Figure 50: Rhinoceros (left) and Grasshopper (right) interactive view of the digital tool

As the user double-clicks on specific components, a GUI is shown for further configuration. In case of the opening component (Figure 51), the user is requested to specify the type of window, which is divided into three typologies: low-, medium- or high-specification. The level of specification of the window is based on the expected thermal performance of the frame and of the glass. By clicking the "apply" button, the physical properties (thermal and carbon-related) are assigned to the geometry generated in the GH/Rhino environment.


Select the desired type of opening and configure it

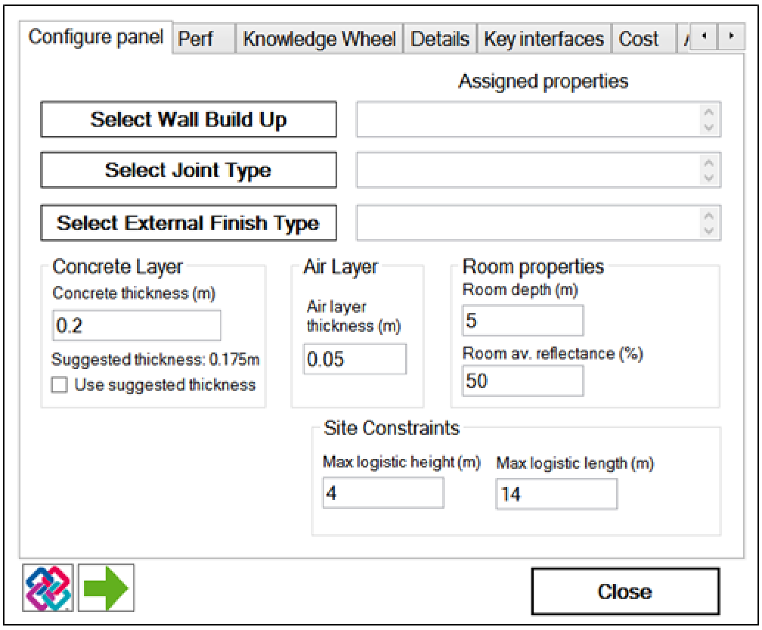
LowSpec

AWS 70 ST.HI

Basic depth	70 mm	Approvals	
Min. face width	84 mm	Sound reduction index [dB]	37
Uf value (s+e)	1.60	Air permeability	Class 4
Max. glass thickness	29 mm	Watertightness	9A
Opening type	Inward	Burglar resistance	RC 1
Surface finishes	Powder / Anodised / Paint / Duraflon / Colour ranges	Wind load resistance	C5/B5

Figure 51: Opening selector

By double-clicking on the panel component, another GUI formed of various tabs is generated. Figure 52 shows the "Configure panel" tab, which is dedicated to the determination of the physical and geometrical features of the panel and its sub-elements.



Assigned properties

Concrete Layer
Concrete thickness (m)
0.2
Suggested thickness: 0.175m
☐ Use suggested thickness

Air Layer
Air layer thickness (m)
0.05

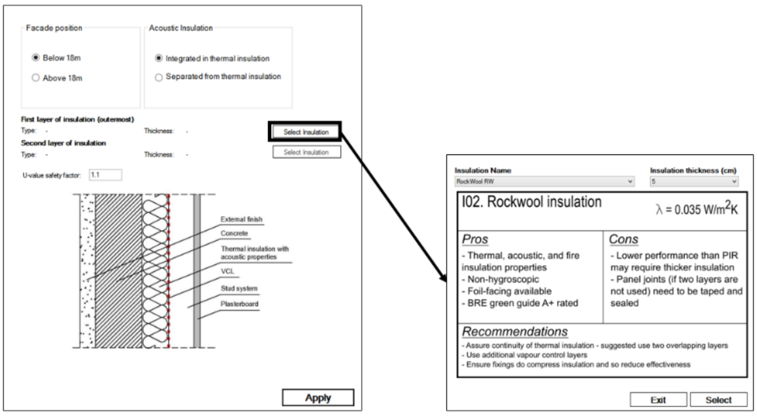
Room properties
Room depth (m)
5
Room av. reflectance (%)
50

Site Constraints
Max logistic height (m)
4
Max logistic length (m)
14

Figure 52: Precast panel configuration tab

The "Select wall-build up" button opens an additional window (Figure 53, left) for the selection of a set of four pre-packaged wall types, depending on two aspects: whether the panel is installed above or below 18m above ground level (for UK fire regulations), and if the acoustic insulation is to be integrated into the thermal insulation or whether it can be decoupled and installed on the back of the plasterboard. The four configurations were studied in collaboration with the internal consultancy team in Laing O'Rourke.

Once the build-up is selected, the type of insulation is determined (Figure 53, right). By clicking on the "Select insulation" button, a list of available standard insulation types and thicknesses is displayed. The list varies in accordance with the type of selected build-up: as an example, if the panel is located above 18m above ground level, only insulation with limited combustibility is available. The available insulation is accompanied by a table reporting the relevant pros, cons and recommendations about the installation of the material.



Facade position
● Below 18m
○ Above 18m

Acoustic Insulation
● Integrated in thermal insulation
○ Separated from thermal insulation

First layer of insulation (outermost)
Type: -
Thickness: -

Second layer of insulation
Type: -
Thickness: -

U-value safety factor: 1.1

Insulation Name: RockWool RW
Insulation thickness (cm): 5

I02. Rockwool insulation
$\lambda = 0.035\ W/m^2K$

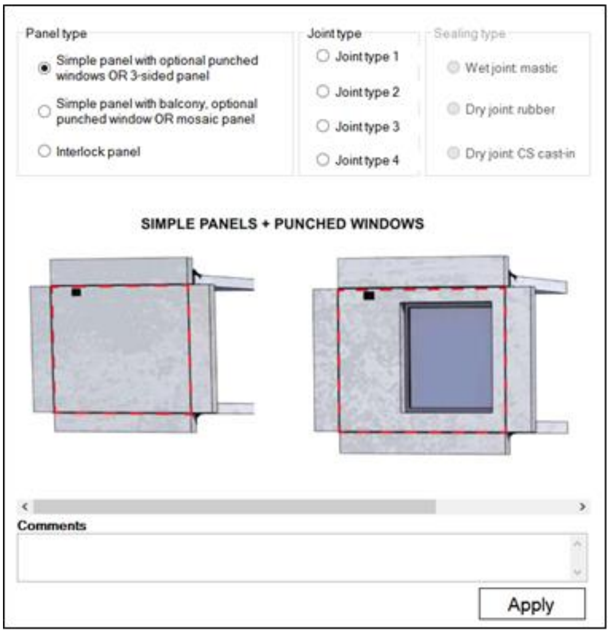
Pros
- Thermal, acoustic, and fire insulation properties
- Non-hygroscopic
- Foil-facing available
- BRE green guide A+ rated

Cons
- Lower performance than PIR may require thicker insulation
- Panel joints (if two layers are not used) need to be taped and sealed

Recommendations
- Assure continuity of thermal insulation - suggested use two overlapping layers
- Use additional vapour control layers
- Ensure fixings do compress insulation and so reduce effectiveness

Figure 53: Wall build-up selector

The “Select Joint Type” window (Figure 54) allows the selection of different jointing strategies both in terms of geometry (e.g. flat, stepped) and sealing type (wet or dry). The configuration is accompanied by a series of suggestions about pros and cons of each choice; the selection of a specific solution will affect the thermal behaviour (by varying the value of the linear thermal transmittance due to the linear thermal bridge) and the embodied carbon of the panel. Specific joint types can accommodate only specific sealing types.



Panel type
● Simple panel with optional punched windows OR 3-sided panel
○ Simple panel with balcony, optional punched window OR mosaic panel
○ Interlock panel

Joint type
○ Joint type 1
○ Joint type 2
○ Joint type 3
○ Joint type 4

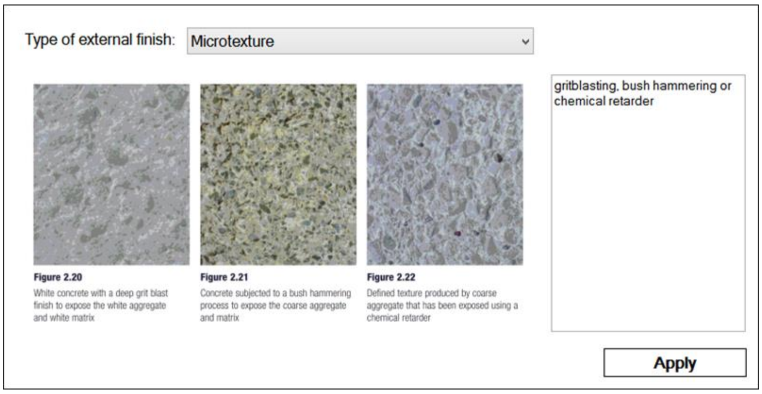
Sealing type
○ Wet joint mastic
○ Dry joint rubber
○ Dry joint CS cast-in

SIMPLE PANELS + PUNCHED WINDOWS

Comments

Figure 54: Joint type selector

The “Select External Finish Type” assigns the finish type to the external layer of the panel. There are five types of external finish that can be selected; those correspond to the currently available standard types of finishes that can be applied in the Explore Industrial Park. If the user/designer desires a specific finish type, the facility should be contacted directly for bespoke design. By clicking the “Apply” button, the selected finish is applied to the panel, thus changing the weight of the panel and its embodied carbon.



Type of external finish: Microtexture

gritblasting, bush hammering or chemical retarder

Figure 2.20
White concrete with a deep grit blast finish to expose the white aggregate and white matrix

Figure 2.21
Concrete subjected to a bush hammering process to expose the coarse aggregate and matrix

Figure 2.22
Defined texture produced by coarse aggregate that has been exposed using a chemical retarder

Figure 55: External finish selector

The “Configure panel” tab also includes the possibility to input the thickness of the concrete layer, if known, or to select the “Use suggested thickness” option to let the tool calculate the concrete thickness based on some past design cases. The tab also allows the user to select the thickness of the air layer, the room’s reflectance and depth (for daylight calculations) and building site-specific constraints to be checked against in the “Knowledge Wheel” tab (Figure 57).

The “Performance” tab (Figure 56) calculates the main indices of performance. The U-value is divided into opaque + opaque-related thermal bridges, glazed + thermal bridges due to the spacer along the perimeter only, and total U-value. The U-value opaque and total also include the contribution of the two bottom brackets via the point thermal transmittance χ. The daylight factor has been calculated in accordance with the Lynes rule [97]:

$$DF = \frac{A_{glazing}\tau_{vis}\theta}{A_{total}2(1 - R_{mean})}$$

where $A_{glazing}$ is the total glazing area, τ_{vis} is the visible light transmittance of the glazing, θ is the sky angle, A_{total} is the total area of interior surfaces and R_{mean} is the mean surface reflectance averaged on the area of surfaces. The embodied carbon is calculated from a pre-built database [102] as the sum of the material weights multiplied by the specific embodied carbon value (kg_{CO_2}/kg). Similarly, the panel weight has been calculated as the sum of the single weights of the components, each one being calculated as the product between their density and volume. The total thickness is the sum of the thickness of each layer (external finish, concrete layer, insulation, air and plasterboard), whereas the cost is calculated as per the relevant "Cost" tab (Figure 60).

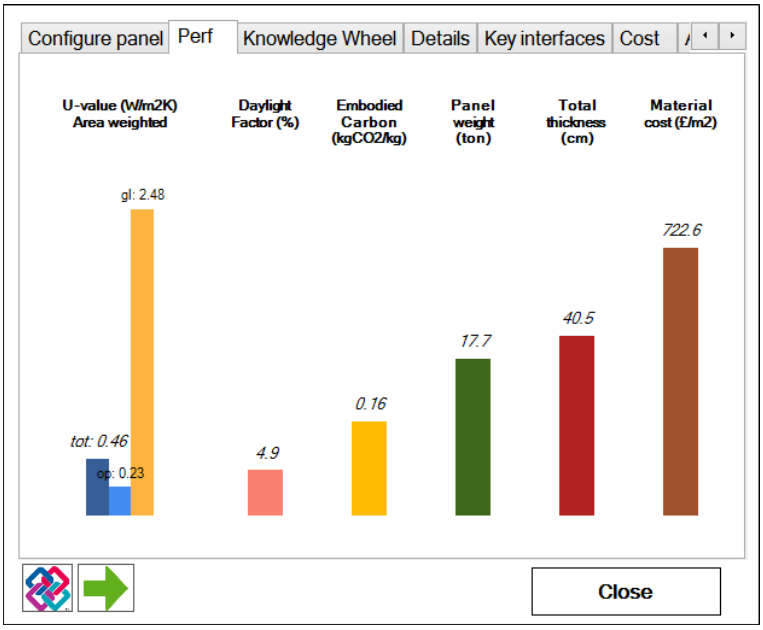


Figure 56: Performance tab selector

The "Knowledge Wheel" tab (Figure 57) shows the knowledge base. It is interactive in that the constraints can turn either orange or red, depending if a specific constraint is considered "soft" or "hard", respectively. Rules can turn orange too depending on whether their application deserves attention (e.g. tool cannot calculate the type of supporting bracket and therefore support from human resources is needed). By clicking on the appropriate text in the knowledge wheel, the user is redirected to the relevant MOKA form, which is stored online. In this way, the user can understand the logic behind the criterion (rule/constraint) and apply corrective actions accordingly.

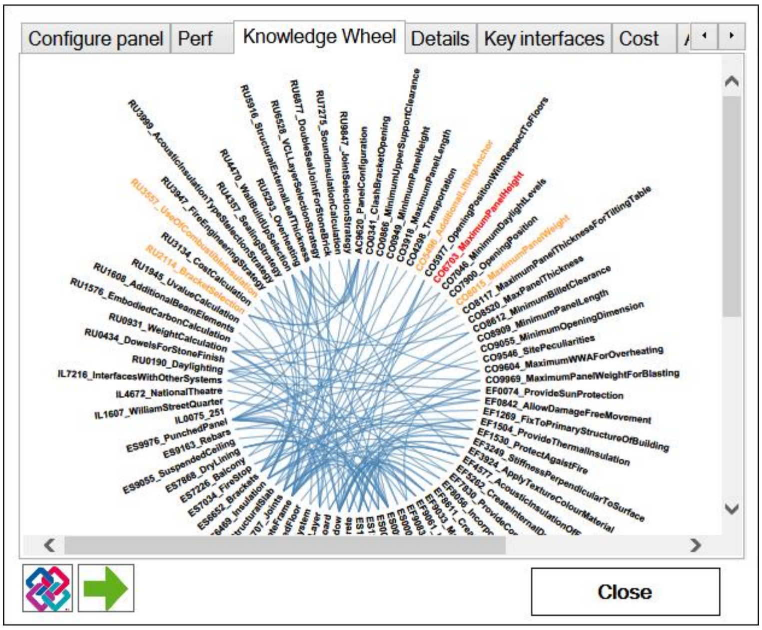
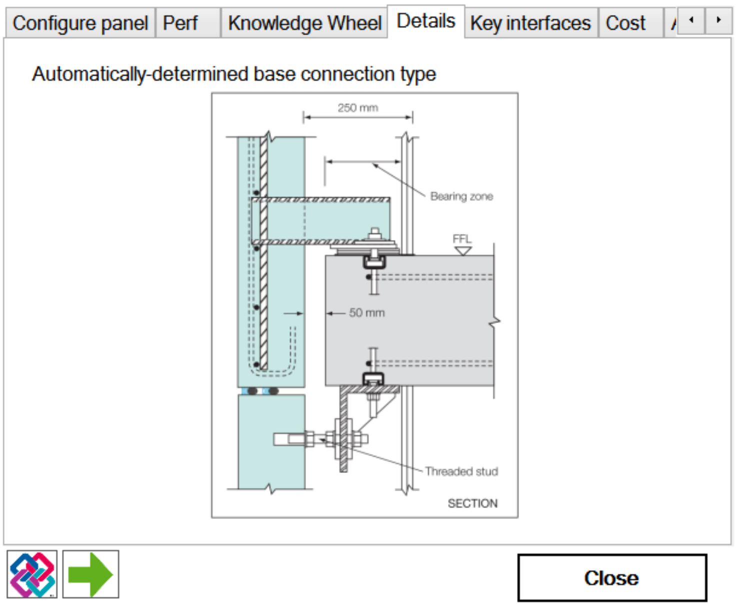


Figure 57: Knowledge wheel tab

The "Details" tab (Figure 58) shows a visual representation of the rule for the determination of the required supporting bracket. The detail is showed to provide guidance to the designer for further detailing in subsequent design stages. If the detail cannot be determined automatically by the rule, a message will be shown and the relevant text in the "Knowledge wheel" tab will turn orange.



Automatically-determined base connection type

Figure 58: Details tab

The “Key interfaces” tab shows an axonometric view of a series of standard details that can be downloaded by clicking on the appropriate hyperlink. The files are in .jpeg extension and they have been developed by the internal consultancy team in Laing O’Rourke.

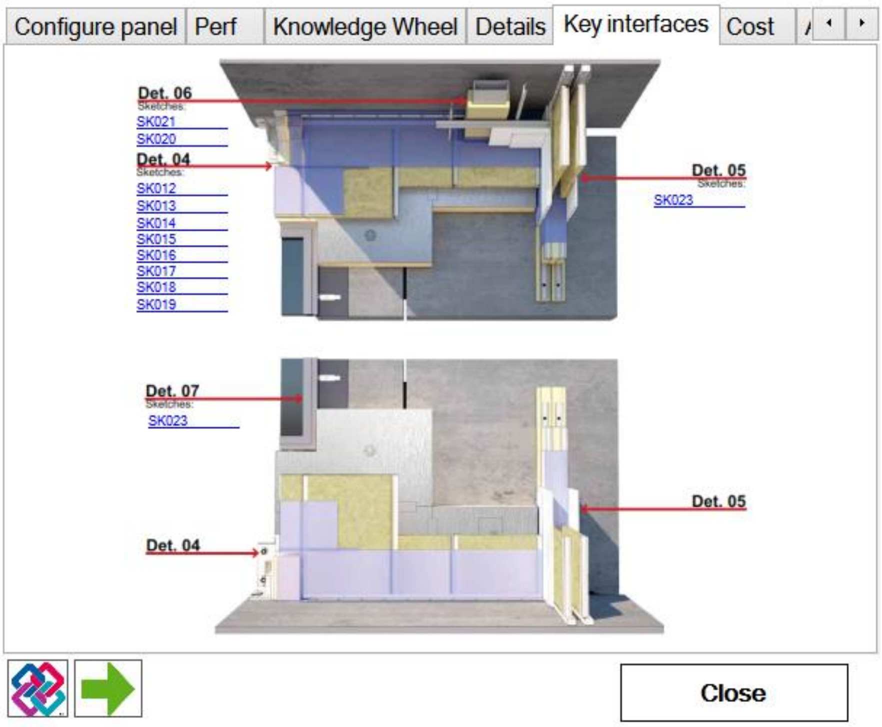
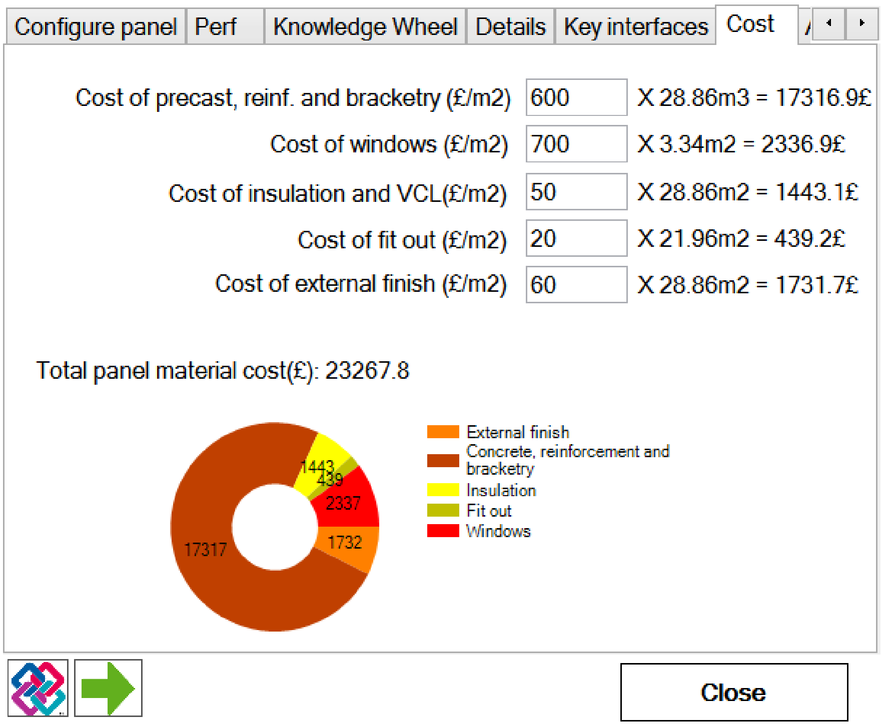


Figure 59: Key interfaces tab

The “Cost” tab displays a breakdown of cost per constituent, whose quantities are automatically calculated by querying the PM. The user is requested to input the values to get the total cost of the panel. The cost is displayed in the “Performance” tab.



Cost of precast, reinf. and bracketry (£/m2) 600 X 28.86m3 = 17316.9£

Cost of windows (£/m2) 700 X 3.34m2 = 2336.9£

Cost of insulation and VCL(£/m2) 50 X 28.86m2 = 1443.1£

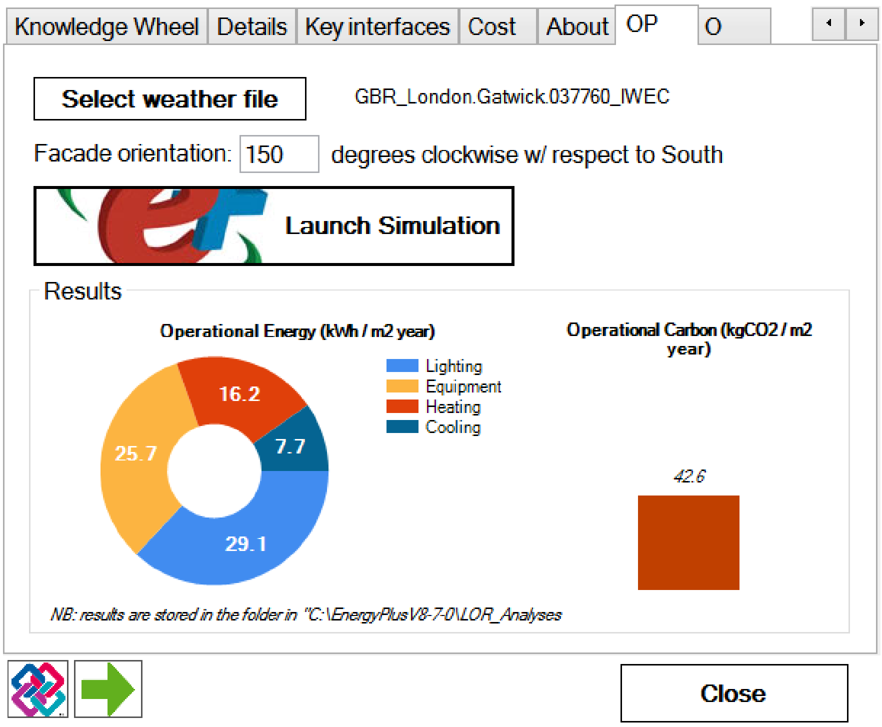
Cost of fit out (£/m2) 20 X 21.96m2 = 439.2£

Cost of external finish (£/m2) 60 X 28.86m2 = 1731.7£

Total panel material cost(£): 23267.8

Figure 60: Cost tab

Finally, the "Operational performance" tab runs a single-zone dynamic energy simulation of the area of interest of the façade. The user is requested to upload the weather file and the orientation of the façade, and launch the simulation. The simulation determines the required operational energy for lighting, equipment, heating and cooling. Lighting and equipment energy is calculated in accordance to pre-determined schedules and power densities that therefore do not take into account for the incidence of different window-to-wall ratios or glass transmittances. Schedules are set for the residential end use, to run the analyses performed in chapter 6. Further work to extend such features is needed. Heating and cooling energy are calculated by considering an air-to-air heat pump with standard seasonal efficiencies of 1.2 and 2.5, respectively. The tool then determines the expected operational carbon by converting the total primary energy by a conversion factor (0.542 kg_{CO_2}/kWh).



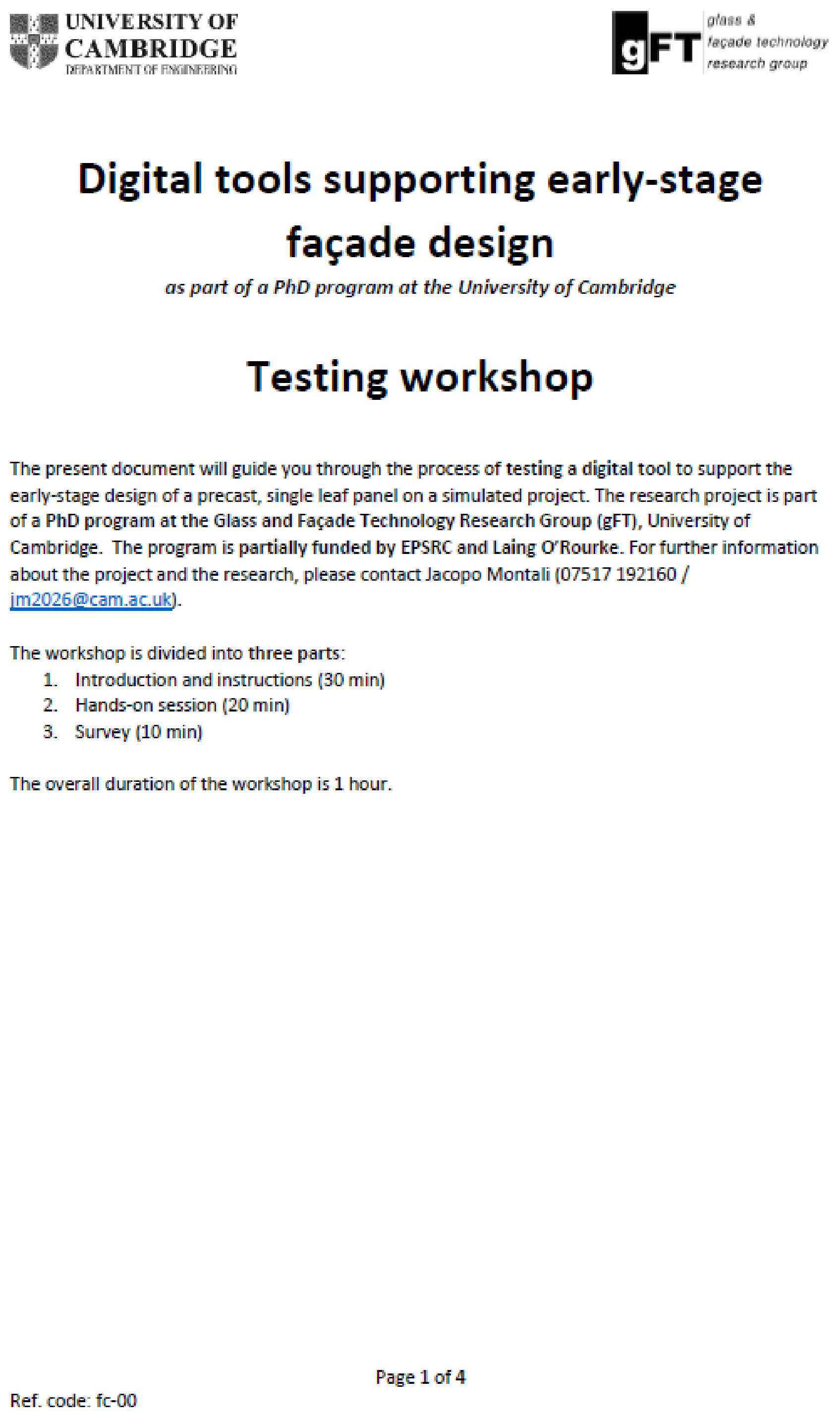
GBR_London.Gatwick.037760_IWEC

Facade orientation: 150 degrees clockwise w/ respect to South

NB: results are stored in the folder in "C:\EnergyPlusV8-7-0\LOR_Analyses

Figure 61: Operational performance tab

Appendix E: Workshop with façade consultants



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gFT glass & façade technology research group

Digital tools supporting early-stage façade design

as part of a PhD program at the University of Cambridge

Testing workshop

The present document will guide you through the process of testing a digital tool to support the early-stage design of a precast, single leaf panel on a simulated project. The research project is part of a PhD program at the Glass and Façade Technology Research Group (gFT), University of Cambridge. The program is partially funded by EPSRC and Laing O'Rourke. For further information about the project and the research, please contact Jacopo Montali (07517 192160 / jm2026@cam.ac.uk).

The workshop is divided into three parts:

1. Introduction and instructions (30 min)
2. Hands-on session (20 min)
3. Survey (10 min)

The overall duration of the workshop is 1 hour.

Page 1 of 4

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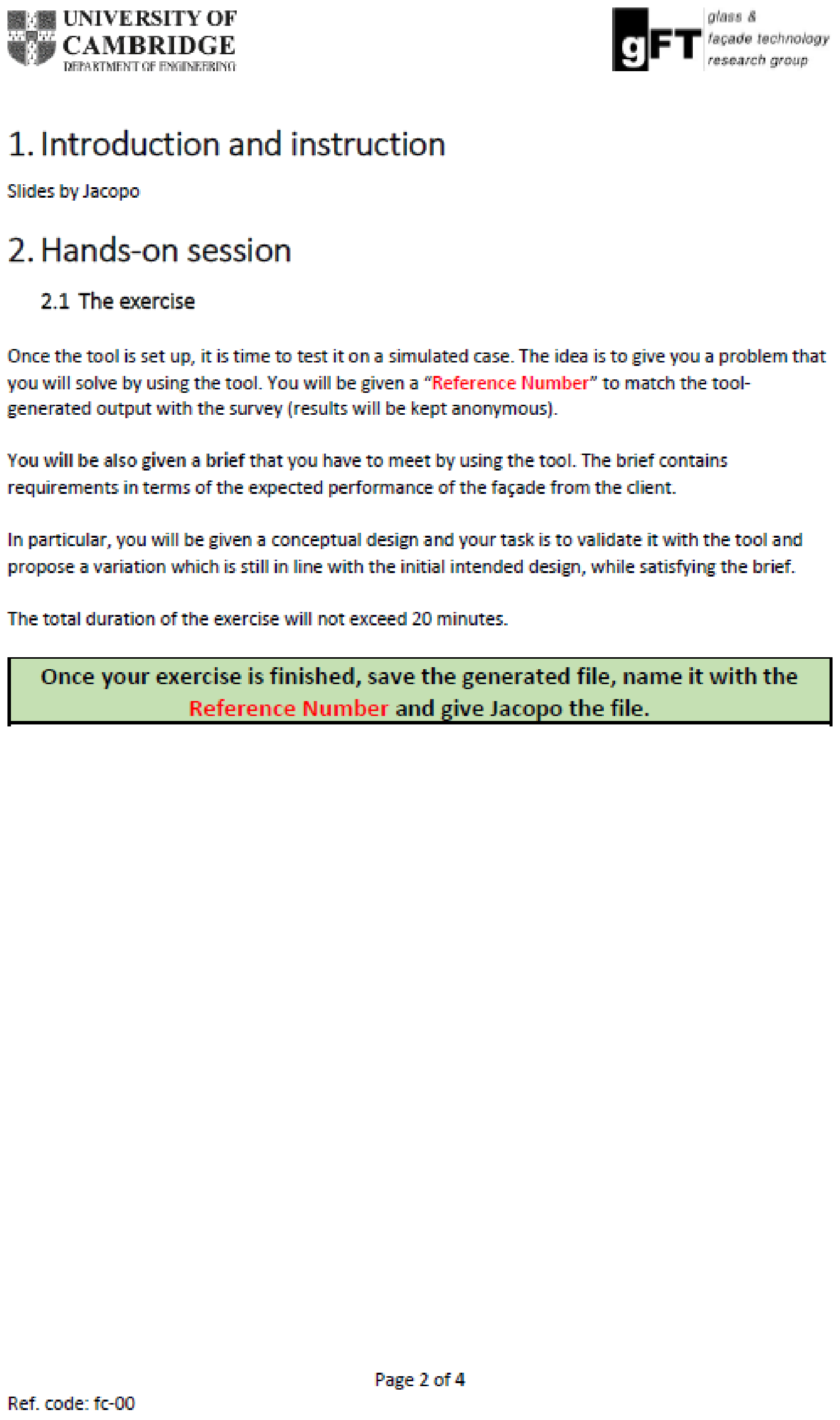

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1. Introduction and instruction

Slides by Jacopo

2. Hands-on session

2.1 The exercise

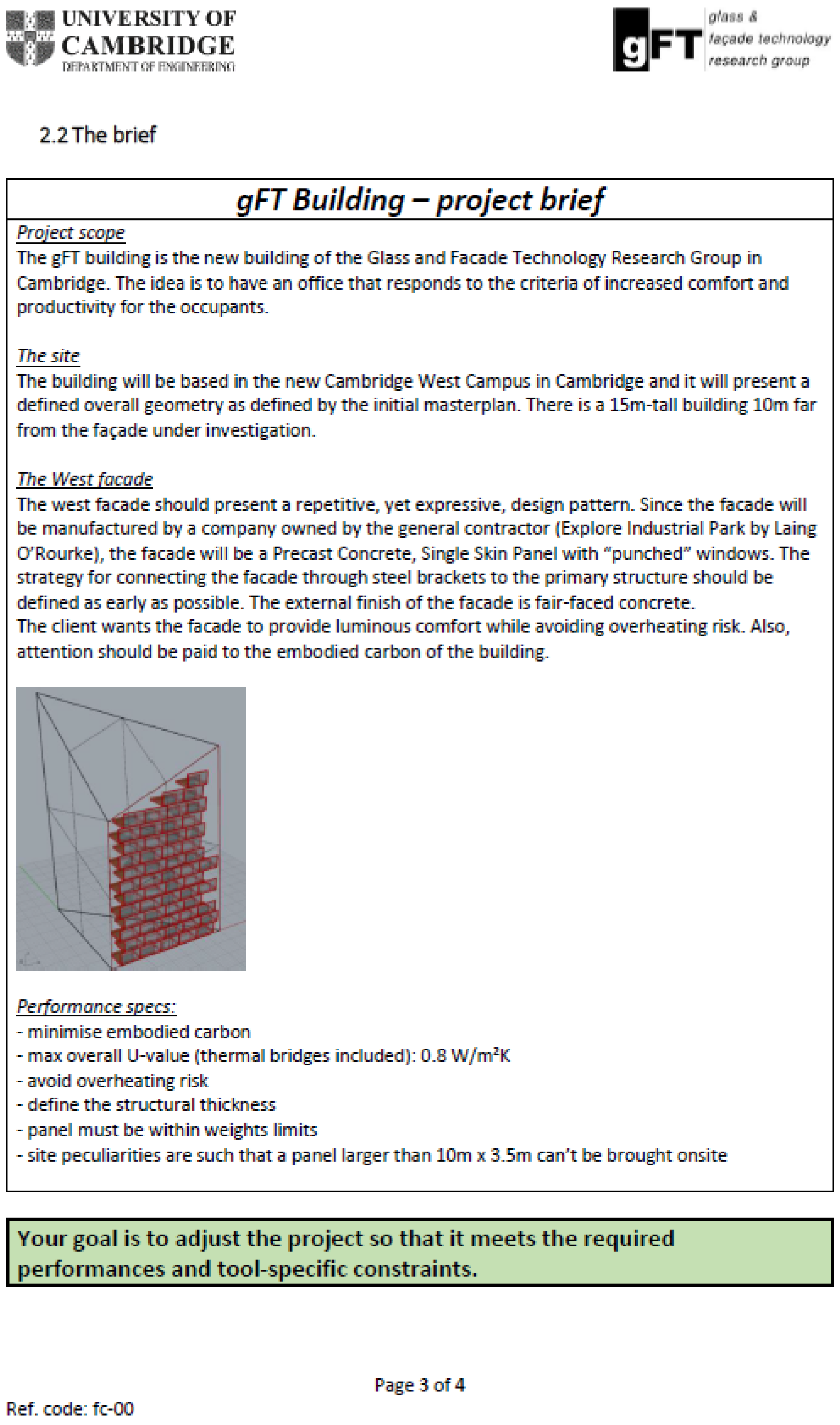
Once the tool is set up, it is time to test it on a simulated case. The idea is to give you a problem that you will solve by using the tool. You will be given a "Reference Number" to match the tool-generated output with the survey (results will be kept anonymous).

You **will** be **also given** a **brief** that you have to meet by using the tool. The brief contains requirements in terms of the expected performance of the façade from the client.

In particular, you will be given a conceptual design and your task is to validate it with the tool and propose a variation which is still in line with the initial intended design, while satisfying the brief.

The total duration of the exercise will not exceed 20 minutes.

Once your exercise is finished, save the generated file, name it with the Reference Number and give Jacopo the file.



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2.2 The brief

gFT Building – project brief

Project scope

The gFT building is the new building of the Glass and Facade Technology Research Group in Cambridge. The idea is to have an office that responds to the criteria of increased comfort and productivity for the occupants.

The site

The building will be based in the new Cambridge West Campus in Cambridge and it will present a defined overall geometry as defined by the initial masterplan. There is a 15m-tall building 10m far from the façade under investigation.

The West facade

The west facade should present a repetitive, yet expressive, design pattern. Since the facade will be manufactured by a company owned by the general contractor (Explore Industrial Park by Laing O'Rourke), the facade will be a Precast Concrete, Single Skin Panel with "punched" windows. The strategy for connecting the facade through steel brackets to the primary structure should be defined as early as possible. The external finish of the facade is fair-faced concrete.
The client wants the facade to provide luminous comfort while avoiding overheating risk. Also, attention should be paid to the embodied carbon of the building.

Performance specs:

- minimise embodied carbon
- max overall U-value (thermal bridges included): 0.8 W/m²K
- avoid overheating risk
- define the structural thickness
- panel must be within weights limits
- site peculiarities are such that a panel larger than 10m x 3.5m can't be brought onsite

Your goal is to adjust the project so that it meets the required performances and tool-specific constraints.

Page 3 of 4

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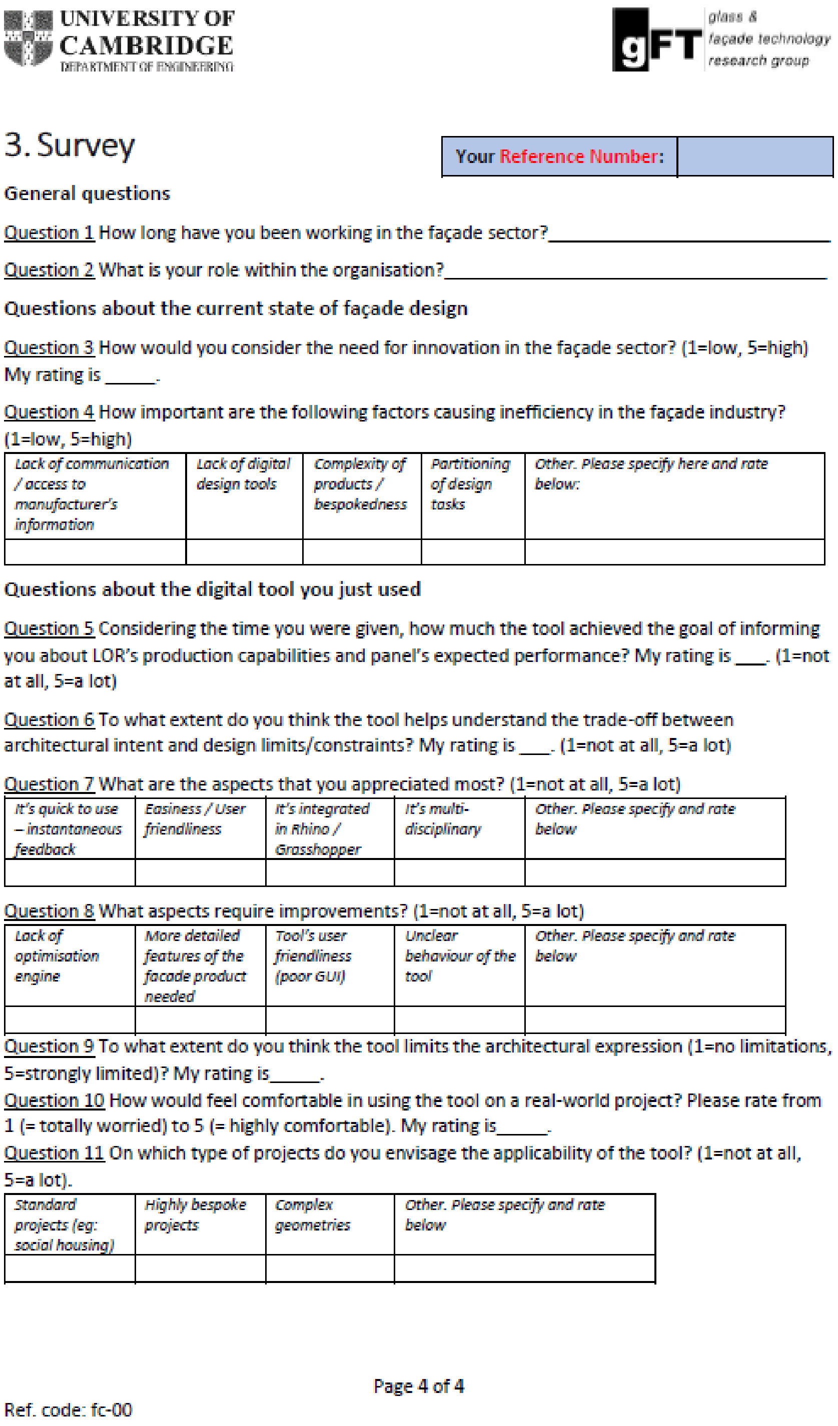

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3. Survey

Your Reference Number:

General questions

Question 1 How long have you been working in the façade sector?________________________

Question 2 What is your role within the organisation?________________________________

Questions about the current state of façade design

Question 3 How would you consider the need for innovation in the façade sector? (1=low, 5=high) My rating is _____.

Question 4 How important are the following factors causing inefficiency in the façade industry? (1=low, 5=high)

Lack of communication / access to manufacturer's information	*Lack of digital design tools*	*Complexity of products / bespokedness*	*Partitioning of design tasks*	*Other. Please specify here and rate below:*

Questions about the digital tool you just used

Question 5 Considering the time you were given, how much the tool achieved the goal of informing you about LOR's production capabilities and panel's expected performance? My rating is ___. (1=not at all, 5=a lot)

Question 6 To what extent do you think the tool helps understand the trade-off between architectural intent and design limits/constraints? My rating is ___. (1=not at all, 5=a lot)

Question 7 What are the aspects that you appreciated most? (1=not at all, 5=a lot)

It's quick to use – instantaneous feedback	*Easiness / User friendliness*	*It's integrated in Rhino / Grasshopper*	*It's multi-disciplinary*	*Other. Please specify and rate below*

Question 8 What aspects require improvements? (1=not at all, 5=a lot)

Lack of optimisation engine	*More detailed features of the facade product needed*	*Tool's user friendliness (poor GUI)*	*Unclear behaviour of the tool*	*Other. Please specify and rate below*

Question 9 To what extent do you think the tool limits the architectural expression (1=no limitations, 5=strongly limited)? My rating is_____.

Question 10 How would feel comfortable in using the tool on a real-world project? Please rate from 1 (= totally worried) to 5 (= highly comfortable). My rating is_____.

Question 11 On which type of projects do you envisage the applicability of the tool? (1=not at all, 5=a lot).

Standard projects (eg: social housing)	*Highly bespoke projects*	*Complex geometries*	*Other. Please specify and rate below*

Page 4 of 4

Ref. code: fc-00