A Tool that Combines Building Information Modeling and Knowledge Based Engineering to Assess Façade Manufacturability

Eleanor Voss, Miss
University of Cambridge, UK, ev236@cam.ac.uk

Mauro Overend, Dr
University of Cambridge, UK, mo318@cam.ac.uk

Summary

Modern façade design projects involve a wide range of materials whose manufacturing and installation impose many different constraints on the design. The façade engineer's role is to manage and apply these constraints to achieve an optimal design. The paper presents a tool to assist façade consultants in the capture, storage and use of 'downstream' design constraints. The aspect of the design process to be targeted by the tool is identified through two process mapping methodologies. The tool captures expert knowledge of the geometric constraints placed on façade panels due to the manufacturing processes. As a demonstration, the tool is applied to real-world façade projects, and is shown to identify areas of the design requiring modification to improve manufacturability.

Keywords: Knowledge, Facade, Manufacturability, BIM

1 Introduction

The façade sector is information intensive, and the development of a good façade design relies on the façade consultant's ability to gather and assimilate large quantities of information regarding the constraints on the design. Using this information, the consultant must identify and communicate the impact of these constraints to the design team. The task is made more challenging by the increasing complexity of façade designs. This complexity arises both from the geometry and from the materials and processes required to produce façade panels to increasingly high-performance specifications.

The primary benefits of Building Information Modelling (BIM) include the efficient storage, access and transfer of design information, and increased collaborative working [1]. As a result BIM has been proposed as a tool to manage and communicate design information[1]. In recent years the construction industry as a whole has increased its use of BIM. However, BIM can be used to improve the end product as well as the design process. The availability of semantic digital design information provides the construction industry with the opportunity to employ knowledge-based engineering techniques[2].

Knowledge-based engineering techniques have previously been used successfully in manufacturing industries to improve manufacturability using Design for Manufacture (DFM) strategies [3]. This has relied partly on the availability of semantically rich digital design information. Fox et al.'s [4] review of DFM and its applicability to the construction industry places the façade sector in the group of sectors to with the potential to benefit most from cost reductions through DFM.

1.1 Knowledge

Knowledge-based Engineering (KBE) in Façade Design

Little of the literature on the application of knowledge-based engineering (KBE) or knowledge management (KM) to the construction industry specifically addresses the façade sector. Much of the work that is available focuses on the service life performance of the façade, in particular thermal performance, moisture control and energy efficiency.

Early work in this area includes the presentation of BEADS (Building Envelope Analysis and Design System) by Fazio et al. [5], a knowledge based system approach to building envelope design. The outputs of the work included a software tool and a knowledge representation framework to hold attributes and values. Although drivers as broad as performance, cost, buildability and maintainability are discussed, the implementation covers performance only. Gowri's research covering the BEADS project suggests that a key area of further work would be to expand the knowledge base to cater for other design issues [6]. Iliescu continued the work on the application of KBE to building envelope design in Concordia University, however, the technique shifted from rule-based to case-based reasoning[7]. Iliesu's work also focuses on the energy efficiency of building envelope designs.

Fazio et al.'s [8] more recent work considers the application of BIM technology to building envelope design. The International Foundation Class (IFC) schema is used to store and transfer design information in a system that incorporates a database of bench mark values of façade performance. The system evaluates design alternatives, partly based on the values stored in the knowledge database. Again, the work only considers thermal and environmental design requirements.

Both Gowri [6] and Iliescu [7] highlight the information intensive nature of building envelope design and therefore the applicability of computers and KBE as information handling tools for the designer. However, the two pieces of work proposed different KBE techniques. Gowri uses rule-based design, and Iliescu a case-based approach, on the premise that the façade sector is a 'weak theory' domain, making elicitation of rules unmanageable. However, both conclude that the application of KBE to the façade sector is beneficial, particularly in the preliminary stages of design.

A key draw back of the case-based technique is the static nature of the database [7]; this indicates that a dynamic database that learns alongside the designer may be preferable. Although this work is not specific to the façade sector, live capture and use of knowledge has been proposed and developed in the CAPRIKON project [9], [10]. This refers to the capture of knowledge during a project in a format that can be used directly on the current project and on subsequent projects. Kamara et al.[9] suggest that 'live capture', as opposed to post-completion capture, increases the reuse of knowledge gained on a project and involves the supply chain with the capture of knowledge more efficiently. The paper also notes that live capture avoids the loss of knowledge when capture is coordinated through post project reviews. This work indicates that knowledge from the downstream supply chain is most effectively captured using a live capture methodology. Project knowledge so captured can be used on both the current project and future projects.

Knowledge Based Engineering and Knowledge Management in the Construction Industry

Although the research community has developed and employed technologies in this area, industry itself has shown less progress. Robinson et al. [11] presents a review of the strategies and technologies used by large construction firms to capture and store knowledge. Those used by the consultancy sector included skills 'yellow pages', intranets, and communities of practice. These in general do not capture knowledge in a computer-interpretable format indicating that although research communities are automating (or semi automating) their capture and use of knowledge, industry is not and still relies on human interpretation.

1.2 Mapping

Façade design and construction is a relatively new sector of the construction industry, as is the role of the professional façade engineer, both in consulting and contracting [12]. In addition, the sector is complex in the of range of materials employed, geometries involved, performance requirements and its multidisciplinary nature. The youth and complexity of the sector suggest that a map of the design process would be a very useful aid to researchers in this field. The main benefits of process mapping suggested by literature include increasing understanding of actor's roles and activities [13], aiding identification of strategic, process and IT requirements [14], or forming the basis for IT systems [15].

The paper partly presents work based on two mapping methodologies. The maps have been used to select a scope for the proposed tool and to understand availability of design information.

Mapping Design Influences

The Design Research Methodology developed by Blessing *et al*. [16] is a structured approach to design research projects. By mapping the influences on design project outcomes, it is possible to identify areas of the design process that could be targeted by the research project. In response, support tools can be developed and tested. This methodology has been employed in the initial phase of the research project to identify the scope of the design support tool.

Mapping Design Processes

Previous work undertaken by the authors [17] include a map of the façade design processes. One benefit of process mapping suggested in the literature is that it form basis for IT systems [15]. For this research, the map has been used to identify packets of knowledge that are non-project-specific and can be captured, stored and re-used.

1.3 Paper Content

The following sections of this paper outline the research undertaken on the topic. Sections 2 and 3 present two maps of the façade design process, one showing the influences on design outcomes and the other depicting the processes themselves. These sections describe how the maps have been used to identify the aspects of the design process that a knowledge-based tool should target. Section 4 provides a description of the tool devised, and section 5 presents two case studies showing the use of the tool on real-world projects. Conclusions and areas for further work are discussed in sections 6 and 7.

2 Design Influence Map Production

The Design Influence map has been developed through an iterative process, drawing on the experience of façade engineers currently working in the façade sector. First an outline map was developed via a series of interviews with industry members. This was then reviewed in an interview with a façade engineering team director, whose comments and modifications were incorporated into the map. The final iteration consisted of a workshop to elicit knowledge from a team of façade engineers and produce the final map.

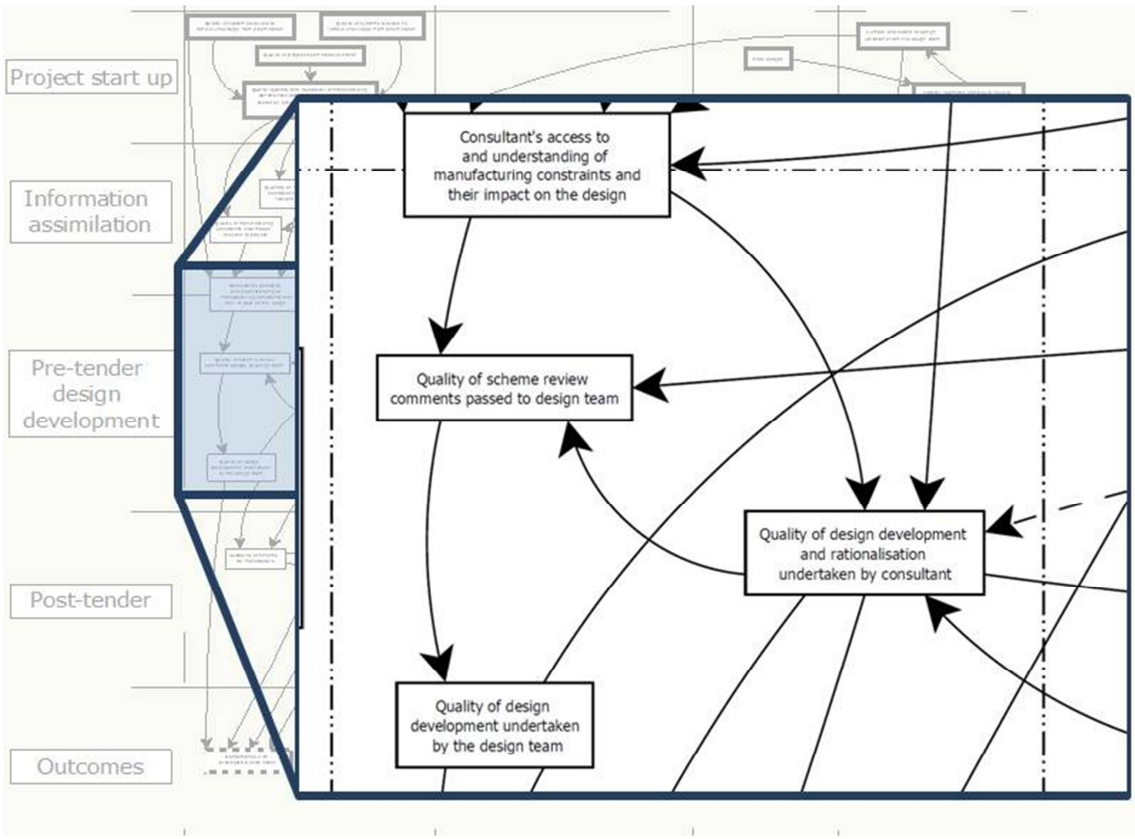

Figure 1: An expanded extract of the Façade Engineering Design Influence Map

Figure 1 shows an enlarged section of the map. Each bubble in the map describes either a design influence or a project outcome. For example, the quality of the scheme review comments passed to the design team influences the quality of the design development undertaken by the design team.

By using the DRM it was possible to identify which factors influence the overall construction cost, and the extent to which the final design conforms with the architect's and client's original design intent. One of the key factors identified was *the façade consultant's access to and understanding of manufacturing constraints and the impact of these constraints on the design at pre-tender design stages* (shown in Figure 1). As a result, capturing, storing, using and re-using manufacturing constraints is the focus of the tool.

3 Mapping Façade Design Processes

As part of previous work undertaken by the author [17], a full map of the façade design and construction process has been developed. For the research presented in this paper, the map was used to identify patterns of use of specific information or knowledge objects. For example, by identifying the repeated use of packets of knowledge that are not project-specific, a system can be developed to capture, store, and make accessible these elements for re-use in subsequent projects. In addition, by assessing when these information objects are re-used, the tool can be developed to encourage users to update the recycled information.

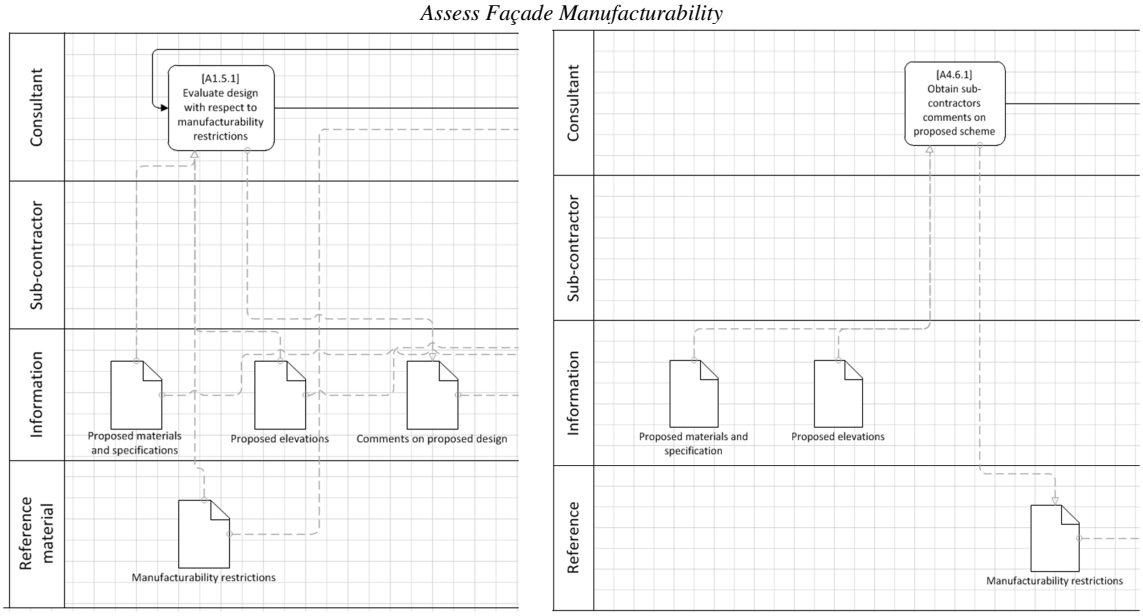

Figure 2: Activities A1.5.1 and A4.6.1

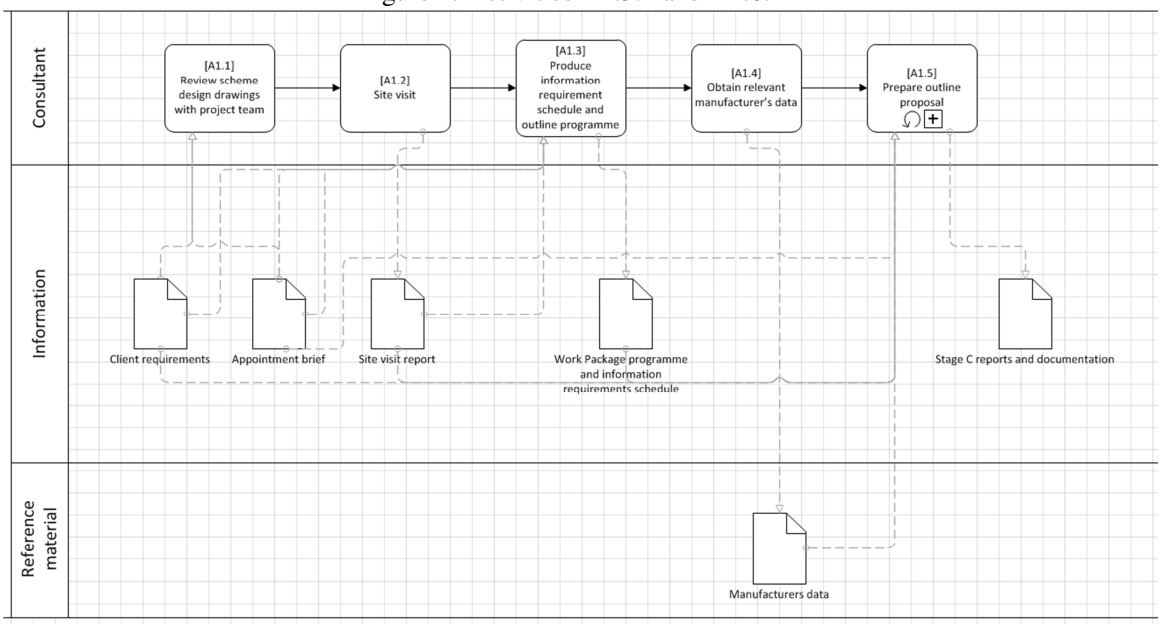

Figure 3: Activities A1.4 and A1.5

The map shows that activity A1.5.1 (Fig. 2) requires knowledge on size restrictions of facade panels to assess the panelisation scheme proposed by the project architect. This knowledge is owned by the consultant and is not specific to the project. Activity A1.5.3 uses the same information for a development rather than a review task. The consultant has the opportunity to update the knowledge during activity A4.6 (Fig. 3), when the same type of information, this time owned by the contractor, is used to review the design.

4 The Proposed Tool

The design outcome influence map discussed in section 2 suggests that both knowledge of manufacturing constraints, and the efficient and effective application of this knowledge by the façade consultant are key factors in determining the success of a project. The process map shown in section 3 indicates that this knowledge is not specific to a particular project and can be re-used. Therefore, the

tool presented in this section has been developed to capture, store, use and re-use knowledge. The tool focuses on knowledge of the constraints manufacture imposes on the façade panelisation scheme.

The proposed system is in prototype form and consists of a series of modules. Geometric design information is stored in the Building Information Model (BIM) in IFC format (element (A) in Figure 4). Details of the extraction and analysis of design information from the IFC database are provided in [18].

The IFC schema is unable to store details of the materials and processes that make up the façade panels in a sufficiently structured manner. Therefore the panel materials are specified by the user using an spreadsheet-based tool developed for the project (element B on Figure 4). The two types of design data (geometric and material) are linked through a labelling system. For example, an attribute of the panel object in the BIM database is the façade type (A, B, B.1 etc.); this corresponds to a façade type specified in the tool. The material options are stored in the re-useable database (element (D) on Figure 4). This part of the database has been populated by extracting the required information from specifications for 30 real-world projects.

Alongside providing the knowledge-based tool with the information required to identify relevant design constraints, the tool generates and updates the project façade typology report, a key (paper-based deliverable) of the façade consulting team during the design stages (element (C) of Figure 4).

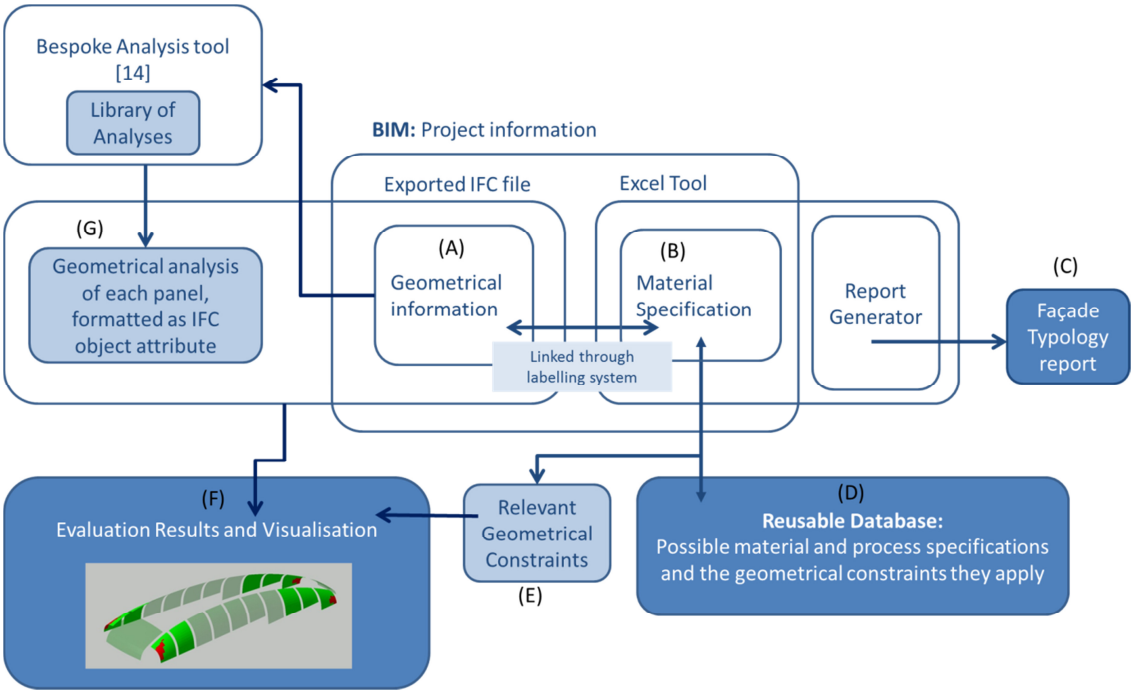

Figure 4: Diagram of the tool

When the user uses the tool to select the materials and processes to be used to make the panel, the tool also identifies the correct set of geometrical constraints. Several different checks may be required for each panel. For example, dimension, curvature and aspect ratio checks may all be performed. To aid this, the re-useable database (element (D) on Figure 4) stores a set of constraints for each possible material or process. As the user selects each material or process for a panel, the tool also identifies a set of constraints. The tool selects the correct constraint (maximum, minimum or range depending on the constraint type) for each check to form a final set of constraints (one for each check type) for each façade panel (element (E) on Figure 4). The constraints stored in the prototype tool have been gathered from interviews with industry members.

In addition to the identification of constraints, the tool provides the user with a storage facility that can be updated or expanded in parallel with a project. This encourages and enables live knowledge capture by facilitating the use of the knowledge on the current project; capture of knowledge as it is identified; and involvement of the supply chain.

The design is evaluated by comparing the constraints to the results of the corresponding geometrical analysis performed on the design data extracted from the BIM database (element (G) on Figure 4). The results of the evaluation can be provided visually, so as to ease communication of the design issue to the rest of the design team (element (F) on Figure 4).

5 Case studies

The following two case studies aim to identify whether the proposed tool can help the façade consultant to identifying panels in proposed panelisation schemes that are shaped or sized in such a way that they either cannot be manufactured, or cannot be manufactured at a reasonable cost.

Oxford Brookes, University Building

The proposed Oxford Brookes University Building has over ten different façade types, each type having many sub-types and each sub-type consisting of several different materials. The materials include among others: glass, with various coatings; fiber-reinforced concrete; and aluminium. The size and shape of these panels vary over the façade area, but to simplify modelling for the case study, a small representative area was selected.

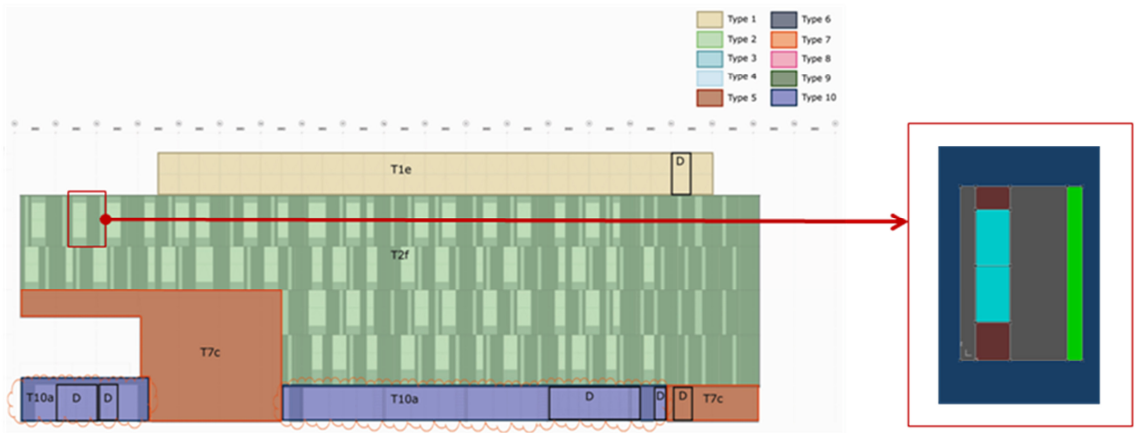

Figure 6: An elevation of Oxford Brookes. The section of the façade used in the test is highlighted with a red rectangle. (Image on left generated by Ramboll Façade Team)

The chosen section of façade was modeled using information from RIBA (Royal Institute of British Architects) Stage C architect's drawings. The RIBA Stage C façade typology report was used as the information source for the materials specification. The tool checked the panel geometry against three criteria: the maximum allowable longer dimension; the maximum allowable shorter dimension; and the aspect ratio (a correct aspect ratio prevents distortion of glass panels during heat treatments). These are constraints imposed by the manufacturing process of the panels.

The tool successfully identified problems with three panels. Both fibre reinforced panels had a maximum dimension that was too long, and, the coloured glass panel was too slender. Subsequent architect's drawings show that these panels were indeed modified, based on the consultant's comments

Park House, Oxford Street

Park House is a large, high-specification combined commercial and residential development in the center of London. The roof panels are glazed using a variety of high-specification treatments and glass coatings.

A key design issue for this project was manufacturing the curved panels. The cold bending technique of forcing the glass into shape without heating is considerably cheaper than hot bending, which requires heating the glass to allow it to sag under its own weight. Therefore it was important to understand the extent of hot bending required, and the zones in which it would be necessary. This information could be used to focus the design development, and to evaluate design iterations.

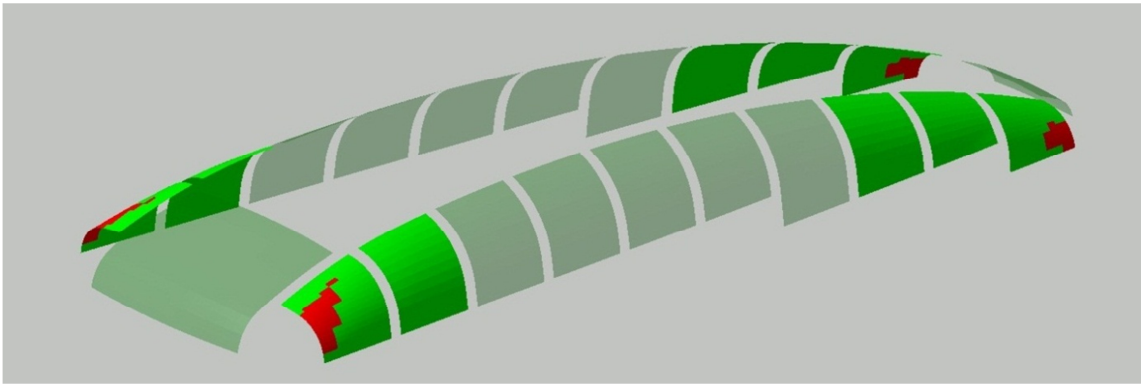

Figure 7: Park House roof; Visualisation of manufacturability analysis results

For the case study, the relevant geometrical information was extracted from the architect's digital model and converted into the required IFC format. The study was performed using preliminary design stage information and so the panels were specified by the façade consultant only as Double-Glazed-Units; no further detail was available at this stage. The tool identified the panels that would require the hot bending manufacturing process. In Figure 7 these panels are highlighted in red.

A comparison of the result from the proposed tool and the sub-contractor's design information shows a close match. The tool underestimated the extent of the panels requiring hot bending by 30% but accurately identified the area of the roof that would require further design development if hot bending was to be avoided. It is possible that the design heuristic should be adjusted if such limited design information is available.

6 Conclusion

A combination of two mapping methods identified *capture and application of manufacturing* constraints as an aspect of the façade design process that could benefit from knowledge-based support.

This paper proposes a rule based, semi-automated manufacturability assessment of façade panelisation schemes. The rule based knowledge management technique is found to be appropriate to manufacturability assessments. Interviews with industry members identified heuristic rules (or 'rules of thumb') that are used by consultants and contractors to highlight manufacturing issues for façades. This makes it possible to capture, in the form of a rule, the required knowledge for the manufacturability assessments.

The proposed modular tool has been tested on real world projects and was able to identify panels with possible manufacturability challenges. The results from the tool matched those generated by industry members. A key capability of the tool is to enable the live capture and use of expert knowledge. The tool automates the identification of manufacturability constraints using the material specification

process undertaken by the façade consultant. In addition the tool stores and supplies these constraints in a computer interpretable form to semi-automate evaluation of the proposed panelisation scheme.

7 Further Work

An important area for further work is to expand the knowledge base to include geometrical constraints on façade panels that relate to maintenance or replacement of façade panels. For example, panels on the upper floors of buildings in tight urban environments may be restricted in size due to the size of the lift shafts in the building that will be used to transport a replacement panel.

The knowledge tool sits within a larger system that performs the required analysis of the geometry as well as comparing this analysis to the constraints selected by the knowledge module presented in this paper. This integration of the models is an on-going project and a key area for further development. In addition, testing of the overall system is planned on a selection of real-world case studies. The tests will aim to build an improved understanding of the system's performance compared to the current industry processes.

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