Prefab Façades – From Prototype to Product?

The Kit-of-Parts approach to a façade design

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Abstract

Building envelopes are not only the prime element of the exterior aesthetic quality of buildings; they have also become a major driver both for building construction cost and operational performance.
The importance of prefabrication is growing in the building industry as it allows faster, high-quality, and cost-effective construction while reducing risks associated with onsite labour. Although prefabrication for structural components is a relatively recent development, it has been widely used in the manufacturing of building envelopes for many years, particularly in the case of unitized curtain wall systems. However, whether using prefabricated components or not, façade design development remains a challenge due to the need for façade engineers to rapidly develop technically viable and financially feasible solutions that achieve the desired architectural design intent. Particularly at the early stages of the design process, the turnaround for multiple iterations is often fast-paced, and abortive work is, therefore, not uncommon.
This paper outlines an approach to addressing this challenge, attempting to bridge the gap between façade design, fabrication, and installation. A new design approach and tools are presented that allow designers to iteratively validate concepts based on a pre-engineered system that is optimized for performance and take fabrication, transport, installation costs, maintenance, and circularity into account. As a result, the tool/design workflow will ensure consistent quality, meeting budgets and timelines while enhancing material efficiency and fostering energy-conscious and circular envelope design approaches.

Keywords

façade design; design for manufacture & assembly; Engineer-to-Order; Kit-of-Parts; product configuration, customization, circularity, sustainability

DOI

http://doi.org/10.47982/jfde.2023.1.04

1 INTRODUCTION

In the last two decades, increasingly strict energy regulations and building standards have led to continuous demand for better-performing buildings that are delivered in increasingly shorter timeframes with reduced budgets (Antunes & Gonzalez, 2015; Otter & Prins, 2001). At the same time, more than any other technology-driven industry, the construction sector has shown a significant lag in productivity and quality assurances due to large amounts of onsite work performed (McKinsey & Company, 2017; Blismas, Pasquire, Gibb, 2006). Designs tend to become multistage design processes involving a variety of design teams, conventionally interacting on a linear design approach basis with iteration loops (Lawson, 1997; Kagioglou et al., 2000). Efficiency and quality outcomes are, therefore, highly susceptible to the degree of organization and engagement of the teams involved. Poor organization often results in inadequate communication and inefficient performance and risk management. On a day-to-day level, it may lead to missed connections and links between the various businesses involved, often coupled with limited talent management, such as deferring to familiar contractors rather than challenging the market supply (Goulding et al., 2015). These factors not only slow down the on-site construction process significantly but also leave room for a subjective interpretation of deliverable quality (The Economist, 2017). This is supported by an intensive literature survey presented by Kassem and Mitchell (2015), who compare studies evaluating factors contributing to poor project performance; the most common denominators causing delays and compromises in quality were found to be communication and planning. The most common results for large-scale projects are time and budget overruns, without ensuring a consistent quality of the deliverables (Assaf, Al-Hejji, 2006).

Learning from other industries and the potential of their production lines, the construction industry grew an increased desire for prefabrication, delivering higher performance components facilitated by increased quality control and reduced risk on site (McKinsey & Company, 2019). While prefabrication allows the designer to achieve better-performing buildings, it requires decision making at early stages with little flexibility in modifying components once they are produced and delivered on-site. The shift towards prefabrication is generally trending in the construction sector (Rocha et al., 2022), but particularly for building envelopes, where prefabrication and system quality play a significant role as performance targets become more stringent.

The performance of the building envelope is fundamental to the overall efficiency and durability of the building. It provides the weather and thermal barrier, solar and glare protection while allowing daylight in and views out of the building (Klein, 2013; Knaack et al., 2007). The building skin has a significant effect not only on the operational energy required and embodied energy/carbon but also fundamentally affects occupant comfort (Pottgiesser, Strauss, 2013; Gasparri, Aitchison, 2019; Zani et al., 2018). In addition to its impact on the performance of the building, the façade also plays a significant role in its appearance and design language, helping to provide architectural identity and uniqueness. This has led to an increasing complexity of the building skin that typically requires inputs from various stakeholders to address multiple competing parameters with conflicting performance and design requirements (Kassem, Mitchell, 2015; Cucuzza et al., 2022; Montali et al., 2019).

Curtain walls are a common approach, particularly to commercial building envelopes. Despite their potential to be fully systemised, in most cases, customized building components are required; the product delivery process is re-initiated from the ground up for each project in the early design stage and at best, existing parts are adapted to the specific design of the building where possible (Montali et al., 2017). This approach to developing a custom system adds time, costs, and risk to the overall delivery process of the façade. A reduced level of customization, for example through the definition of standard and optimized system types, may decrease the design effort and the delivery process but must guarantee a broad range of variability in order to fulfil architectural freedom and design intent. This paper identifies the main design parameters that can be optimized by using a bespoke toolset, and it presents a façade Kit-of-Parts (KoP) developed within the scope of this research initiative.

2 BASIS OF RESEARCH

Typically, the design of a building and its envelope is an iterative process in which, starting from an architectural idea, various technical consultants such as façade, structural, mechanical, environmental, daylight, acoustic and fire engineers provide input that leads to the generation of further design iterations. Through this process, a technically feasible solution that adopts and incorporates established performance requirements is developed – ideally without significant impact on the design intent. In a secondary assessment, which typically occurs at a later design stage, a specialist contractor would be added to an additional iterative process in which the technical feasibility is assessed from a fabrication, installation, and maintenance perspective as well as in relation to cost (Figure 1A). This linear approach does not connect the expertise of the different teams at a level that can facilitate a feedback loop to allow technical comments to influence the design early in the process. Instead, it primarily allows for the integration of feedback once the design stage is complete (Boswell, 2013), resulting in compromises in design, performance, and cost. Integrating continuous feedback in design concept stages would allow the design team to make informed decisions and balance parameters from an early stage, requiring less costly re-work and iteration. The proposed design approach (Figure 1B) is more interactive, involving all teams with their different expertise from the beginning, permitting an informed decision-making process during the design stage rather than the conventional iterative review approach.

A - Conventional design approach

B – Integrated circular design approach

FIG. 1 Façade design workflow. A) Typical linear design workflow currently implemented. B) Proposed continuous design workflow.

As an example, in the early stages of the design, a construction expert is prone to pinpointing choices that can prevent additional expenses at a later stage, while a procurement manager is better equipped to understand how to cut material expenses (The Economist, 2019), which means both provide valuable input from different perspectives. Implementing this information at very early design stages can help to identify key performance parameters, technical and fabrication limitations, and cost drivers to reduce pivotal design iterations. When implemented across various projects, this could reduce the budget needed for design iteration, shifting it towards quality delivery of the product itself (*i.e.*, the façade).

There are multiple ways of ensuring early-stage implementation of cross-functional information. The main objective is to provide enough information to the architect prior to the completion of the conceptual design, which can be achieved by direct involvement of the engineering team and façade contractor. However, this would suggest that all teams involved have to be established and available from the earliest stages of design. A more efficient and independent method to support the architectural design team is to establish tools that assist and inform during the design process, using continuously updated information provided by the engineering team and façade contractor. These tools offer benefits to the design process by enabling not just engineering-driven, cost-effective decision-making in the project's initial phases but also by efficiently optimizing collaboration among diverse engineering teams and specialist contractors. This is expected to improve the quality of design and reduce material use and cost, as well as fabrication and construction time.

3 METHODOLOGY AND RESEARCH

The goal of this paper is to investigate the conventional approach used in façade design and present an integrated approach addressing the problems inherent to this iterative, linear process. The research focuses on developing an interactive toolset that facilitates the implementation of innovative façade workflows and technology.

3.1 INNOVATIVE FAÇADE TECHNOLOGY: KIT-OF-PARTS

The concept of kit-of-parts design has already been partially introduced to façade engineering. In Europe, the curtain wall market is dominated by system providers with specific profiles and various typical details that enable architects to design conventional envelopes that are sized based on load tables, i.e., approximate profile sizes can be dimensioned at an early stage in the design without relying on a specialist engineering input (Kassem, Mitchell, 2015). This allows designers to resolve typical details; however, most projects still require customization. In North America, contractors commonly use their in-house bespoke systems that typically rely on custom dies for every project. Although fabrication occurs off-site, the design of every project is highly customized and could benefit more from the potential offered by prefabrication.

Typically, throughout the design process of a building, various options are explored and engineered by the design team to validate ideas. For the development of curtain walls, this typically means iterations of grid sizes, geometries, material combinations, and additional components that might add loads to the curtain wall structure (e.g., solar shading) (Boswell, 2013). Although essential for an iterative design approach, this process of performance validation is time-consuming, inefficient and requires significant resources for simple iterative tasks. Furthermore, it is typically done in an isolated manner for every project without considering learnings from previous projects and designs.

3.2 APPROACH

The Kit-of-Part (KoP) approach employed by the authors enables an architect-led design team to validate design options through digital design tools based on a pre-engineered set of components. The set of engineering tools incorporated in the web-based user interface allows the architectural team to explore several façade options during the early stages of the design (i.e., concept and schematic phase). Set details, samples, and pre-tested components help the designer speed up the selection and testing process. In addition, it allows the design team to achieve the desired performance and ensure consistent quality throughout a broad portfolio of projects. From an owner's perspective, the KoP reduces risk and helps maintain quality while providing increased cost certainty throughout design, fabrication, shipping, and installation. Specific constraints on panel sizes, geometry, and use of material guide the design process towards a solution that is optimized for performance but aims to find sweet spots in the supply chain to achieve economically effective solutions.

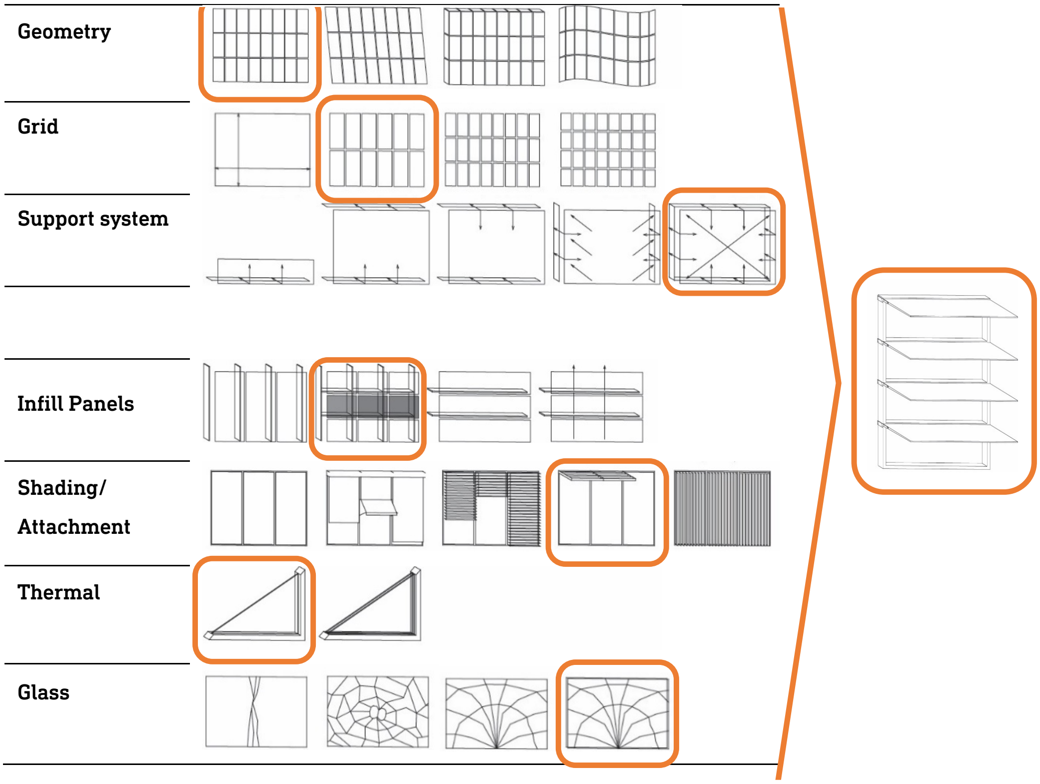


FIG. 2 Technical categories for KoP approach with exemplary decision-making process: Flat geometry, large-scale grid, four sides supported, horizontal infill profile, glass infill panel, horizontal shading attachment, double glazing, heat strengthened -laminated glass.

This integrated circular design approach is based on the idea of breaking down a façade into its fundamental elements, where a multitude of options are provided for each element. The categories start with broader topics like geometry and grid, and narrow down to details like frame sizes, materials, and additional components like solar shading elements (Figure 2). The design team can use the various categories and options to create proposals and concepts. The tools developed are based on the same process, guiding designers through each step in a logical workflow, allowing them to select the option that best matches their design intent within each category while receiving performance and cost feedback on the implications of each selection.

4 RESULTS

4.1 TOOLS

The authors have developed a digital toolkit that allows a design team to pre-engineer the unitized curtain wall based on a variety of factors. The KoP design workflow consists of five engineering tools that are interconnected and integrated into one user interface. The calculation methods and overall workflow presented in this section are currently under beta testing, and the web-based interface is under development. The engineering tools are based on US codes and industry standards such as ASCE 7-16 for load combinations, ASTM E1300 for glass design, AAMA TIR-A11-15, and Aluminium Design Manual for mullion design, as well as NFRC 100-200 for thermal calculations. Overall system performance (e.g., air and water leakage, accommodation of movements, fire resistance) is based on industry guidelines and technical notes such as AAMA (American Architectural Manufacturer Association), ASTM and CWCT (Centre for Window and Cladding Technology).

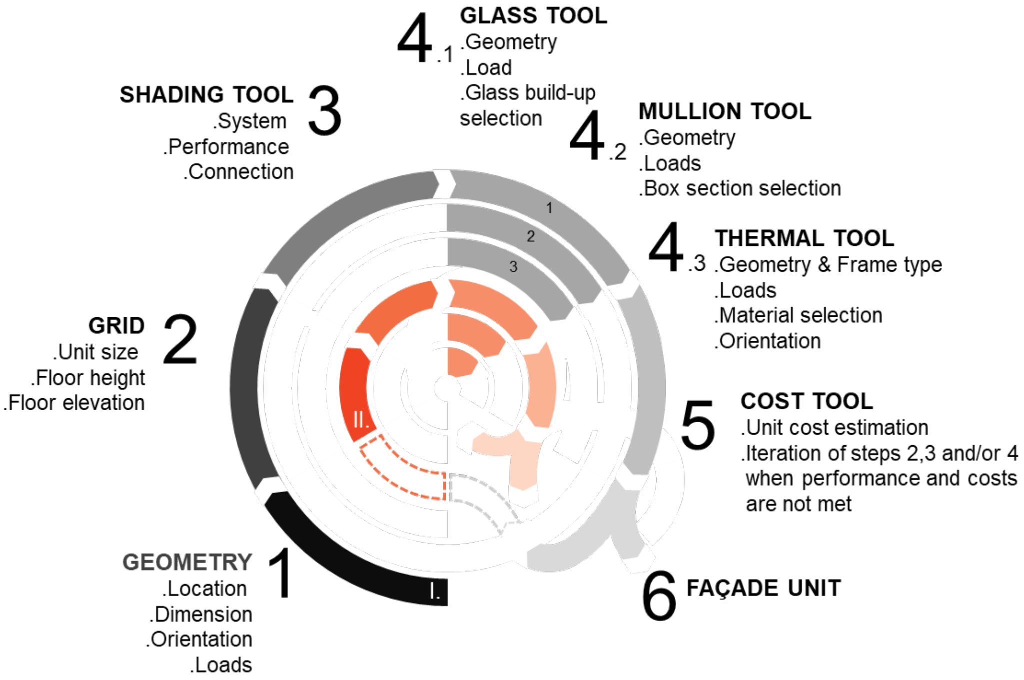


FIG. 3 Tool functionality map. Streamlined design process allows for design iterations (orange) when cost estimates exceed budget without disturbing the overall workflow.

Figure 3 shows a schematic of the workflow for the component-based approach that has been applied for the development of the KoP.

The designer is guided step-by-step through translating the design intent into KoP façade elements and engineering tools, consisting of a structural calculator for framing elements and glazing, a thermal calculator and shading performance evaluation (developed by Loisos + Ubbelohde). For each design iteration, the cost tool runs in the background and provides real-time feedback to the designer on whether the proposed solution remains within the specified project budget.

The tool workflow begins with a series of project-related questions, such as location, building use and orientation, building and façade dimensions, number of wall types, project complexity, and façade budget, to define a baseline façade and cost. The tool will be able to assess and generate a vertical planar façade with a regular rectangular grid. Once the general information is entered in the tool, the designer can generate a façade unit through the unit configurator by defining the unit width, height, number of intermediate framing elements, and infill materials (e.g., glass, shadowbox, aluminium panel, GFRC). As shown in Figure 4, the user can set up a single unit with multiple infill materials (e.g., glass IGU and metal panel). Alternatively, a fully transparent or a full spandrel unit can be chosen, as well as a multitude of other material configurations. If the project comprises multiple unit configurations, the users can create and save these different units and apply a percentage of coverage for each unit across each façade orientation of the building.

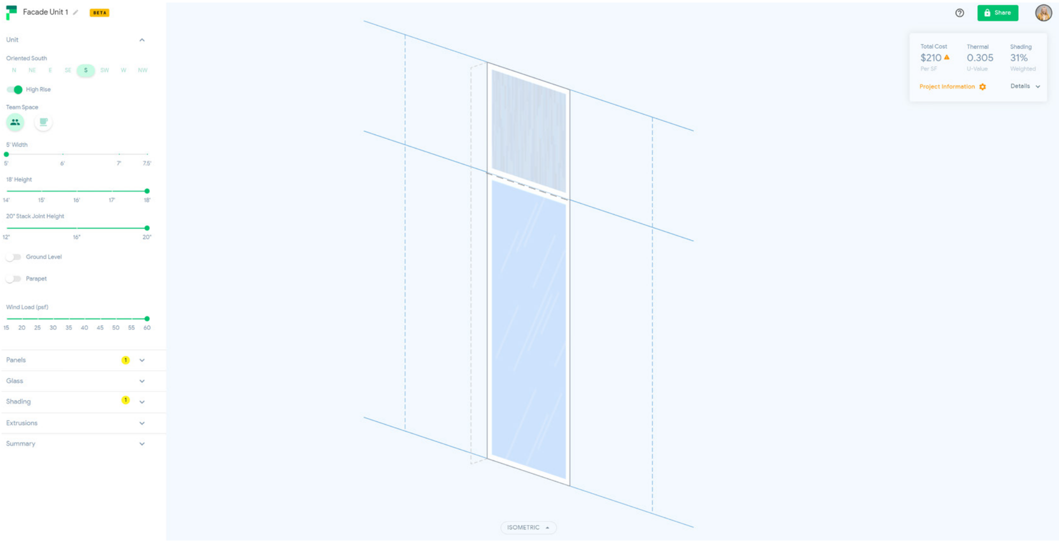
In parallel, the designer can generate and evaluate the effectiveness of various solar shading systems such as horizontal/vertical louvres, external blinds or perforated meshes for different façade orientations. Based on design intent and performance goals (e.g., daylight, view, glare), the user is then able to select the most appropriate shading strategy in combination with specific glass treatment (e.g., solar/low-e coatings, frit). Geometry and material information are automatically transferred to the pre-engineering tools for the façade performance assessment, which are provided as the final output.

Typically, mullion depth is driven by loads and span, while mullion width is primarily driven by shading attachment requirements. As soon as span or loading criteria (either wind load or shading attachment load) exceed the deflection or stress limit for one mullion size, the next larger size will be used. However, an optimization tool allows to reinforce aluminium mullions with steel to choose a smaller mullion size. Percentage-based cost feedback is provided for these options so that sizing decisions can be made conscientiously if a more slender appearance is desired. The mullion cost is influenced by the amount of aluminium used, the thickness of the flanges and steel reinforcements if required. This might mean that the minimum structurally sufficient design may not necessarily be the most economical option.

A similar approach is used for sizing the glass build-up. Based on wind loads, code, and performance requirements, i.e., safety, acoustic and thermal performance, as well as the design intent, the tool generates the most feasible and cost-effective glass build-up. Overall glass build-up (thickness and assembly) and size (width and height) can significantly impact overall façade cost, so the cost tool is based on a pre-verified supply chain.

Outputs from the previous tools feed into a thermal calculator tool that provides the U-value calculation for the typical units across the façade. Typical details (e.g., mullions, stack joints) and centre of panel (CoP) U-value for each material and combination included in the KoP were simulated using (NFRC-compliant software) Bisco and imported into a database. The tool extracts frame and CoP thermal performance values and calculates the system U-value using an area-weighted average method according to NFRC and EN standards. With the thermal tool calculator, the user receives live feedback on how the façade unit performs thermally. This information is provided based on modification of opacity ratio, frame size, material choice, and level of insulation. In addition, by inserting the percentage of coverage for each unit, the user can evaluate the overall thermal performance of the façade and compare it with specified, code-based targets to meet overall building performance requirements.

In order to assist the design team in developing a façade within budget, the KoP design tool incorporates a cost tool into the workflow. The cost tool provides a cost range per square foot of façade considering general façade configuration items such as direct costs, e.g., material, crating, and transportation costs, but also more project-specific elements such as fabrication, engineering, installation, and project management costs.


Facade Unit 1 BETA

Oriented South: S

High Rise

5' Width

18' Height

20" Stack Joint Height

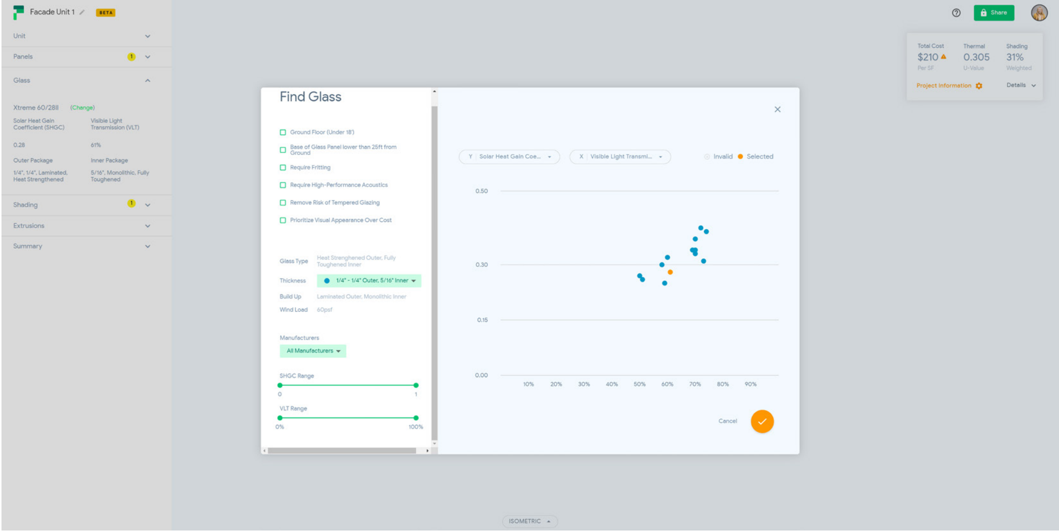
Wind Load (psf): 60

Total Cost $210 Per SF

Thermal 0.305 U-Value

Shading 31% Weighted

1


Facade Unit 1 BETA

Glass

Xtreme 60/28II (Change)

Solar Heat Gain Coefficient (SHGC): 0.28

Visible Light Transmission (VLT): 61%

Outer Package: 1/4", 1/4", Laminated, Heat Strengthened

Inner Package: 5/16", Monolithic, Fully Toughened

Total Cost $210 Per SF

Thermal 0.305 U-Value

Shading 31% Weighted

Find Glass

☐ Ground Floor (Under 18')

☐ Base of Glass Panel lower than 25ft from Ground

☐ Require Fritting

☐ Require High-Performance Acoustics

☐ Remove Risk of Tempered Glazing

☐ Prioritize Visual Appearance Over Cost

Glass Type: Heat Strenghened Outer, Fully Toughened Inner

Thickness: 1/4" - 1/4" Outer, 5/16" Inner

Build Up: Laminated Outer, Monolithic Inner

Wind Load: 60psf

Manufacturers: All Manufacturers

SHGC Range: 0 – 1

VLT Range: 0% – 100%

2

FIG. 4 Façade configurator interface allowing for an eased design process due to linked informative tools. 1. Upper – Unit configurator, 2. Bottom – Glass calculator.

All materials, as well as the profile and shipping cost information, are currently being implemented into a database specific to the KoP supply chain. Project-specific costs are calculated based on economic analysis of historical project data as a percentage of the material and shipping costs based on the main characteristics of the project that is being developed, such as project size, geometric complexity, number of wall types, and project timeline. The cost tool operates in the background and can provide live feedback to the designer for any change generated in the unit configurator or shading tool. As a result, the designer can understand and validate the cost impact of a design decision and be conscious of cost drivers.

Based on the output of the various tools discussed, an optimized solution integrating performance and cost while providing a simple and fast approach to exploring alternates and their implications is generated. All tools are combined into a façade configurator application with a visual interface, as illustrated in Figure 4. All developed tools, such as geometry, glass, shading, mullion, and thermal, are integrated and linked to one interface, allowing an easy and fast way of exploring different design solutions and combinations while keeping the original design intent.

In addition to the performance and cost outputs, the tool produces a set of typical reference details, including typical mullion sections, stack joints, and bracket attachments (Fig.5). The graphic outputs generated by the web-based application can be downloaded and help the design team with the production of project specific façade drawings.

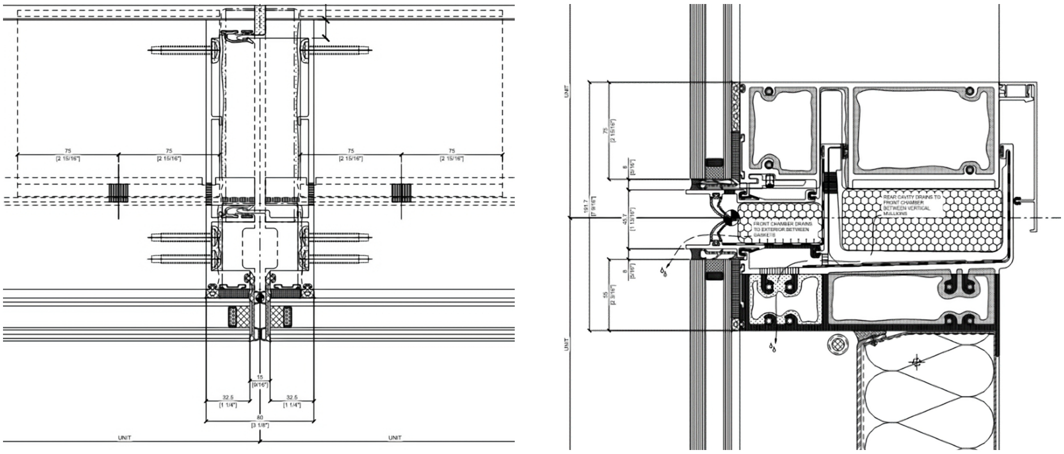


FIG. 5 Typical KoP façade details. Left – Typical mullion, Right – Typical Stack Joint.

4.1.1 Environmental Performance

In addition to performance and cost, sustainability is another emerging design directive which has been implemented into the KoP approach. Environmental impact in the building sector has traditionally only focused on reducing operational energy. More recently, alongside the traditional focus on building energy consumption, there has been increased attention on the influence of embodied carbon in construction materials across various life cycle stages (Bach, Mohtashami, Hildebrand, 2018). Within the KoP approach, materials have been assessed in terms of Global Warming Potential (GWP) and the total non-renewable primary energy (PENRT) through the production life cycle stages (A1-A3). The assessment results can be translated to the KoP tools by highlighting materials with lower embodied carbon results, for example, wood-based infill products.

Circularity is also a core principle of the KoP to emphasize long-lasting materials that can circulate through different future reuse options. For instance, recycled aluminium profiles show significantly lower embodied carbon values than original material, and they can be recycled without being downcycled. Additionally, circular design is not only considered on a material level, but also on a system level. The system's construction considers dry connections, mechanical fasteners, and, overall, joints that are easily disassembled. Throughout different case studies (Deniz and Dogan, 2014; Mule, 2012; Durmisevic, 2006), it was proven that ease of disassembly translates to ease of reuse and recycling, therefore allowing for different options that bring the components back into the loop. As part of the development of the tool, it was further found that using standard-sized products, connections, and modular design eases the path to re-life instead of recycling. An aluminium profile has a typical service life expectancy of approximately 75 years, while the glazing unit in the system tends to have a service life of 25-30 years. Using details with standardized profiles that allow for glass replacement to avoid premature recycling of aluminium units increases the overall service life of the façade and significantly lowers embodied carbon.

FIG. 6 Façade component library. Visualisation of implemented design solutions to support virtual decision-making tool.

4.2 FAÇADE COMPONENT LIBRARY

To support project team engagement with the KoP approach, a physical sample library was created in addition to the digital content and database implemented into the tool. This library contains small-scale samples of the typical materials that are part of the KoP, as well as physical representations of profile shapes and sizes. Full-scale 3D printed extrusion elements that can be disassembled help designers understand configuration ranges and allow them to assess profile sizes based on loading, spans and joint sizes depending on the loads, and type of chosen shading. Joint sizes are affected by loads as well as material choices, with heavier and larger shading elements requiring larger brackets, which in turn lead to increased joint widths. Like the KoP itself, the library is based on flexible modules that can be re-arranged to accommodate the needs and focus of each project team (Figure 6). Design teams can use the space as per their needs and combine materials and finishes in physical form to represent the configurations that are assessed in the configurator. This can occur in parallel, which again helps to increase efficiency within the process as the design team is not reliant on lead times for materials to be provided; instead, immediate access to the library from the beginning of the project allows the team to compare products, materials, and finishes with every iteration of the design.

Prior to final engineering and system design, a visual mock-up is typically used to assess profile and unit dimensions, dimensional relationships of the geometry as well as material combinations and finishes. When a bespoke system is designed, the visual mock-up is often a physical representation of the profile sizes but made from a more rapidly constructible, readily available material (e.g., timber) to evaluate visual aesthetic and detailing but not structural integrity or performance. Depending on the project size, various forms of visual validation are possible within the KoP approach; starting from a digital mock-up that allows the team to walk through in virtual reality while validating material finishes in the material library to container mock-ups with full-size panels and complete visual mock-ups with full representation of a portion of the building envelope. Depending on the complexity of the project, as well as budget and timeline constraints, the appropriate form of visual validation can be chosen. Pre-validation of the materials reduces the need for multiple visual mock-ups, resulting in time and cost savings.

Even for the larger scale mock-ups, the advantage of a KoP approach over a bespoke façade system approach is that typical profiles will be available, and the mock-up can be built with actual profiles faster than through a traditional approach.

FIG. 7 Visual mock-ups for visual material review: Glass viewing.

FIG. 8 Performance mock-up: Dynamic air and water infiltration is tested by using a wind turbine to generate dynamic wind loads.

4.3 PERFORMANCE TESTING

Physical testing of the building envelope, in addition to analytic validation, is typically required due to the complexity of façade performance criteria. For this reason, a performance mock-up using project-specific profiles, infill materials, and interfaces is typically assembled to replicate the worst-case scenario and tested for air and water tightness as well as structural and seismic performance. In traditional building projects, this performance test is a major factor both in terms of design and timeline of a project as well as cost. In contrast, because the KoP always uses the same set of base components, teams can avoid project-specific testing because the system is pre-tested for a worst-case scenario under a defined range of conditions. Currently, the tool kit is applicable to projects within a specific geographic location (San Francisco Bay Area) and building type (Commercial building, risk category II and III). Performance testing is carried out for the most complex conditions to allow results to be scaled and applied to any project that is designed using the KoP approach and within the geographical boundaries and defined limits of the tool kit.

While performance testing is outlined in national and international standards, validation of visual quality is more complex to assess in a consistent manner, as it is partly subjective. To make sure that a consistent quality can be achieved through a broad portfolio of projects and across multiple suppliers, a review procedure has been developed to pre-assess and validate manufacturers through the entire supply chain for the KoP. Only pre-vetted vendors can supply materials for the KoP, which increases the level of quality achieved in the façade components. Visual quality is pre-assessed and evaluated in terms of replicable parameters. These adhere to proven industry guidelines where available, e.g., Hadamar guidelines for visual assessment of glass. For other materials and components, visual assessment guidelines are developed based on similar parameters, ensuring that materials can always be viewed under consistent conditions and according to parameters that maintain an objective review. With this approach, the KoP process employs more resources upfront while risk impact is lower and allows for a streamlined process per project with significantly reduced risk by benchmarking quality at an early stage.

5 CONCLUSION

The KoP approach outlined in this paper translates the integrated continuous design process typically used in other industries for the development of commercial products and efficiencies related to it, to the design of building envelopes. Façades are usually designed and produced on a 'prototype' basis where each design is specific to the building and the performance requirements associated with it. The digital tool-based design approach allows project teams to work in an integrated process without having to wait for input from each specialist discipline, as would be the case in a traditional linear process. Façade performance is pre-engineered through the developed tools, which, combined with the validation of the supply chain, results in consistent quality, reduced cost, and improved circularity throughout a broad portfolio of designs and projects.

Given that the tool is still in its beta state, with the web-based application under development, the implementation of the application to a typical project design workflow remains to be verified. The main challenge will be to guarantee sufficient variability and flexibility to meet the design intent envisioned within the boundaries of the KoP. Another challenge is related to future proofing the day-to-day operation, particularly maintaining calculation methods in line with code modifications, updating the material component library, and keeping cost and supply chain information up to date.

As a result, however, the façade as a component or a product — rather than a prototype that requires testing for every application — has the potential to be delivered in consistent quality, within an understood budget and timeline, and with significantly higher efficiency of material use, leading to a more energy conscious and circular approach to envelope design.

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