Market survey of timber prefabricated envelopes for new and existing buildings

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The building sector has revealed a need for process optimization, mirrored by the ongoing discussion around industry 4.0 and increasing automation in building design and construction. Within this context, the prefabrication and standardization of building elements provide interesting opportunities for optimizing the construction process. Off-site fabrication of building envelope and systems can provide significant advantages in terms of process, quality and safety management. This paper presents an outline of state-of-the-art building opaque envelope prefabrication, with particular focus on timber building skins, through a collection of best practices both in the field of building retrofit and new construction. This research is a result of shared research interests and synergies among the Institute for Renewable Energy at Eurac Research and the Innovation in Applied Design (IAD) Lab at the University of Sydney. Results highlight current limitations of envelope prefabrication and outline development opportunities both at technical and production process level. These findings and the conclusions we draw from them will set the foundations for expanding the adoption of an industrialized fabrication approach in the construction environment.

Keywords: Envelope prefabrication, off-site manufacturing, envelope retrofit, timber construction, construction process

1 Introduction

In recent decades, the construction sector has been evolving with the aim of achieving increased sustainability objectives. This has been pursued through the adoption of life cycle design methods, as well as application of industrial production principles and advanced manufacturing concepts (Aitchison 2018). In practice, research and technology development activities are translating these objectives into a so called “lean” production approach, which is generally acknowledged as the combination of sustainability in resource management (human and physical) and productivity optimization.

The sustainable use of resources in the building sector can be implemented through: use of certified environmentally friendly materials, design of energy efficient construction solutions, or even the adoption of a circular economy design approach. The latter is based on the re-use of building elements at the end of service life to minimize environmental impact and optimize the building economic cycle (Tebbatt Adams, et al. 2017). Productivity in the building sector is low if compared to other manufacturing branches and the average global economy (McKinsey Global Institute 2017). The authors propose prefabrication as a means to pursue both sustainability and productivity in a synergic manner, which is able to boost construction productivity through the following: (i) coordinated work of several players along the value chain; (ii) enhanced execution speed and quality; (iii) advanced technological design effort (iv) and, investment optimization, with a focus on process innovation. Off-site fabrication of building elements (or prefabrication) allows for a deliberate shift of works towards the manufacturing site rather than the traditional construction site, according to the degree of industrialization that is foreseen for a specific real estate development or renewal operation (Smith 2010). The adoption of this approach can increase productivity up to 50-60% (McKinsey Global Institute 2017). However, it is important to point out that it is not enough to move building production from the building site to the factory, rather, it is also important that the manufacturing mindset be adopted to harness the full value proposition of prefabrication.

The market survey presented in the following section is focussed on the prefabrication of timber building envelopes. This scope is viewed as a crucial research priority given the high tempo at which structures and systems are already able to be built and produced.

1.1 Aim and Scope

This work is the result of research synergies among the Institute for Renewable Energy at Eurac Research and the Innovation in Applied Design (IAD) Lab at the University of Sydney, whose activities focus respectively on designing energy efficient envelopes for building retrofit on the side of Eurac, and advanced prefabrication methods for high rise timber buildings on the side of the IAD Lab. In particular, this paper focusses on prefabricated envelopes conceived on a timber-based structure (the core expertise of both institutions). The use of timber responds well to both the sustainability and productivity challenge in the construction sector. Indeed, wood is a carbon neutral and renewable resource, in line with the current de-carbonization objectives set by the European Commission (European Parliament 2010), as well as highly compatible for prefabrication and industrialized production. In addition, it is lightweight and characterized by high thermal performance, features that make it even more suitable for use in the building envelope.

The aim of this research is to advance knowledge in the field of envelope prefabrication and construction process optimization both for existing and new buildings. This is done through a technical solution market survey to outline main achievements, limitations and perspective research and technology development in the field.

2 Taxonomy of building envelope prefabrication

Envelope elements prefabrication dates back to the 1950s and is generally associated with the post-World War II need for rapid housing supply to the population. In the latest years, the concept has been refined to describe *the production and manufacturing of construction elements off-site to the highest possible degree, so to minimize works to be performed on-site, apart from mere assembly operations* (Smith 2010). The 1990s saw a rather systematic push of industrial production concepts into the building sector, such as mass customization or lean manufacturing. However, these concepts are having a hard life within the construction market, struggling to be truly integrated in the value chain of building production that persists in being rooted on an analogue based approach (McKinsey Global Institute 2017).

It is commonly agreed that the attempt to drive the development of the construction sector towards an industrialized approach to building production is based on the huge perceived advantages of off-site working, such as: increased productivity in terms of time and cost, increased workers safety, enhanced quality of the output, together with a more sustainable use of resources in terms of construction site logistics, components manufacturing and waste minimization. Prefabrication is based on three core promises: quality, cost and timeliness. These challenges have been a recurring idea in housing and construction since the last two centuries, still without being totally fulfilled in terms of objectives. More recently, the concept of prefabrication has been enriched with environmental sustainability and possibility to integrate personalized features (Aitchison 2018). Among those, multifunctional envelopes include a set of possibilities to integrate system elements, allowing for enhanced energy performance of the building (Babich, et al. 2018).

As demonstrated by the successful example of unitized glazed curtain walls in tall construction, the use of standardized components within the envelope of a building allows for a quick, reliable and safe installation phase, shifting product's detailed engineering work to the manufacturing site (protected environment) and significantly reducing the need to work at height. Despite the widespread use of unitised façade elements in high-rises, the mid to low-rise building sector is characterised instead by the use of traditionally-conceived multi-layer opaque envelopes, which allow for excellent energy performance but still relies on the traditional ad-hoc and site-assembled approach to fit the case-specific features. This lack of uptake implies a consistent rise in production costs, due to the impossibility to access an economy of scale.

3 Methodology

The authors analysed a set of case studies acknowledged as best practices examples by the technical and scientific community, both in the field of new construction and retrofit operations. Cases are presented in brief to allow the reader a general understanding of system technical features, then compared along the reveal construction management dimensions, such as (i) use of fixed scaffoldings; (ii) level of prefabrication, according to the need to perform additional work on the prefab wall unit after its installation in place; (iii) technical/economic convenience with respect to traditional, single components based, construction techniques. In the case of new buildings, the technical/economic convenience parameter has been discarded from the analysis, in light of the significant market differences connected with the geographic locations of the presented buildings (Europe vs. Canada, as seen in 3.2).

3.1 Retrofit case studies

Europe’s existing building stock is much older, on average, than that of Australia and even the USA. Despite construction traditions that date back many centuries, most of the existing buildings are affected by severe underperformance from an energy and comfort point of view. A number of collaborative research projects in the last decade have concentrated their design effort in the field of existing buildings retrofit with advanced technological systems that can integrate renewable energy sources (RES) and actively contribute to European decarbonization objectives. In this section, the authors present a collection of projects in the field of envelope retrofitting using prefabricated elements, characterized by high technology readiness level and real demo-case sites, followed by a comparison of the most significant prefabrication related criteria (see Table 1).

TES Energy façade project (http://www.holz.ar.tum.de/forschung/tesenergyfacade/) developed an off-site fabricated modular façade to be applied in residential building retrofit (Larsen, et al. 2011)(Fig. 1 and 2). The approach has been successfully developed and released in two versions TES (2009) and smartTES (2013), the latter also integrating system components in façade modules. The project is based on a systemized digital workflow that embraces the whole value chain from measurement, to planning, fabrication and mounting. The main technical features can be summarized as follows: (i) large panel size, to cover one storey of the building; (ii) timber framed insulated cassettes; (iii) external cladding, sills and reveals as well as steel weather profiles; (iv) integrated windows.

Fig. 1 TES EnergyFacade project – process digitization (source: Gumpp & Maier)

Fig. 2 TES EnergyFacade project – panel installation (source: Gumpp & Maier)

iNSPiRe – Systemic Energy Renovation of Buildings (http://inspirefp7.eu/) developed an off-site fabricated modular system for efficient energy renovation of residential buildings, with the aim of minimizing construction works on site for the deep renovation of façade, roof and energy systems (Fig. 3 and 4). This project has further developed the results achieved in the TES Energy façade project, focusing on system integration. The designed façade has been successfully deployed in two different case studies. The main technical features can be summarized as follows: (i) large panel size, to cover one storey of the building; (ii) timber framed insulated cassettes; (iii) external cladding, sills and reveals as well as steel weather profiles; (iv) integrated windows. The iNSPIRe façade also integrated multifunctional system components, such as micro heat pumps, heat recovery units and related ducts (Dermentzis, et al. 2014) (Ochs, et al. 2015). Some hydraulic and aeraulic components have been integrated in a dedicated system shaft, prefabricated as well and integrated within the façade allowing to bridge the building apartments at different floors.

4RinEu – Reliable models for deep renovation (http://4rineu.eu//) makes a step further with the aim of supporting the use of off-site fabricated renovation packages with design methodologies and reliable business models (Babich, et al. 2018) (Fig. 5 and 6). As for the case of TES EnergyFacade and iNSPire, this façade is equipped with the same layers and components before leaving the construction site. However, the construction site shown in the pictures below has benefitted from process optimization not only during the manufacturing phase, but also for construction site management. In fact, the production facility is located in a short distance (3-4 hours) from the site and modules were delivered just-in-time for installation.

Fig. 3 iNSPIRe façade installation sample, external side view (source: Gumpp&Maier)

Fig. 4 iNSPIRe façade installation sample, internal side view (source: Gumpp & Maier)

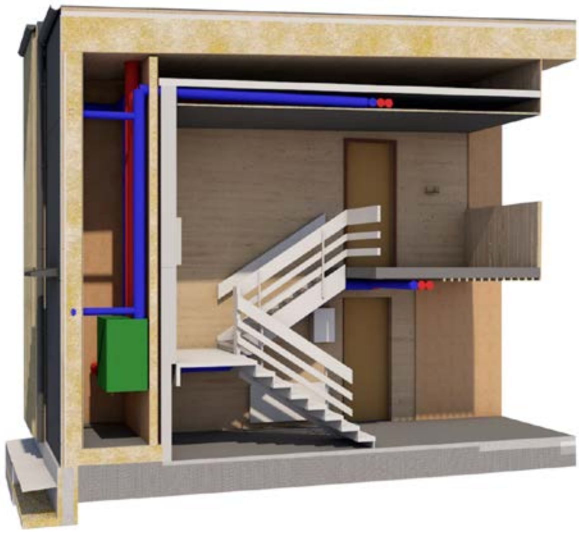

Fig. 5 4RinEU façade design process (source: Municipality of Oslo)

Fig. 6 4RinEu façade installation sample, external side view (source: Municipality of Oslo)

H2020 SINFONIA project - Low Carbon Cities for Better Living (www.sinfonia-smartcities.eu), has worked on the development of an extensive set of energy saving measures spanning from smart transportation systems to envelope retrofit solutions (Fig. 7 and 8). In this frame, prefabricated module types have been chosen by the design team as façade concept, designed and applied in several construction sites in Bolzano (Italy). Authors believe that there is potential for replicating this approach in future works – even if some conceptual design work still needs to be performed to eliminate the need for onsite work completion. Main technical features that characterize this solution can be summarized as follows: (i) TJI timber frame structure, with massive studs applied as external frame and double T shaped composite timber elements applied as intermediate reinforcement, to confine soft insulation material; (ii) regulating layer, made of compressible insulation material applied at the back of the prefabricated module and covered with waterproofing layer - this work is performed offsite and allows to speed up the installation process; (iii) connection system to the existing slabs based exclusively on T shaped metal plates; air and water tightness fixing applied manually between the panels after their installation; (iv) external cladding installed on-site, as in traditional construction.

Fig. 7 SINFONIA project – panel installation (source: Benedikter Arkitekten)

Fig. 8 SINFONIA project – panel production (source: Benedikter Arkitekten)

Table 1: Retrofit case studies comparison according to relevant prefabrication criteria. The technical/economic convenience is evaluated through a benchmark to an average price for advanced façade systems, fixed at approximately 2x the price of a traditional external insulation with ETICS.

Case study ID	Fixed scaffolding	Prefabrication level	Technical/economic convenience
TES EnergyFacade	Yes – lifting crane + scaffolding	High – all layers included	Average cost, the cost is above average when active system components are integrated
iNSPiRe	Yes – lifting crane + scaffolding	High – all layers included	Cost above average, due to integration of active system components[1]
4RinEU	No – lifting crane + mobile construction platform[2]	High – all layers included	Average cost, the cost is above average when active system components are integrated
SINFONIA	Yes – lifting crane + scaffolding	Medium – external cladding is installed onsite	Average cost, room for improvement in the production process

3.2 New construction case studies

Prefabrication of the envelope for timber construction has seen an increased interest in the last two decades, as it allows for quickly covering of the indoor volume and so protecting timber elements from weather agents since the very first days on the construction site (Gasparri, et al. 2015). In addition, the rise in average building height has created market need for envelope solutions that can be installed in a short time and guarantee high workers´ safety level. This paragraph presents a short collection of best practice examples in the field, proposing a simple comparative analysis of the most significant prefabrication related parameters (see Table 2). Differently from the retrofit case study collection, economic parameters are not included, as the geographic marketplaces in which the buildings are standing are not directly comparable.

[1] In this case, higher costs are partly justified by the fact that this project brought to market a façade technology that was still a prototype until it was developed within the project frame

[2] The construction site is a two storey building, so the lack of scaffold is also facilitated by the specific site features

Holz8 building in Germany (2011) is a residential building composed of massive timber components, with preassembled external walls. The prefabricated components are made of the following: (i) CLT load bearing structure; (ii) insulation; (iii) windows and shutters. The façade system is highly prefabricated, but joints between wall units require manual completion from the outside with the use of scaffolds.

LifeCycle Tower One in Austria (2012) has been designed with the aim of reaching Passivhaus standards despite guaranteeing reduced construction time through prefabrication. The prefabricated wall components are made of the following: (i) timber frame support, free from any load bearing function; (ii) insulation and watertight layers; (iii) external cladding; (iv) windows. The façade system has a medium degree of prefabrication, as the watertight layer and the cladding were applied on site through the use of scaffolds.

Ywood «L'Ensoleillée II» building in France (2013) has been developed with the aim of providing clients with flexible solutions characterized by reduced construction time and cost. The prefabricated wall components are made of the following: (i) CLT load bearing structure; (ii) insulation; (iii) external cladding and (iv) windows. This façade system is highly prefabricated, even if vertical joints are completed on the construction site, acting from mobile platforms. A limited use of scaffolds was needed to complete building corners.

Fig. 9 Façade installation process for the Holz8 building in Bad Aibling (source: www.huber-sohn.de)

Fig. 10 Installation of LCT ONE façade system through scaffolds (source: www.creebyrhomberg.com ©Darko-Todorovic|Photography|adrok.net)

Brock Commons building in Canada (2017) has been designed with the aim of constructing the whole envelope without the use of scaffolds. This case study is not a timber-based technology, even if the design phase has seen the use of timber as a possible option. However, it is interesting to include the case in the review as it presents interesting elements in perspective for timber-based application as well. This façade is made of steel stud wall elements, which are hanged onto concrete floors through adjustable connectors as in curtain wall façade. This façade system has a high degree of prefabrication, as the panels were delivered with all layers to the construction site. However, if on the one hand, works on the envelope have actually been completed without any need to act from the outside of the building, the lack of scaffolding led to a bitumen based manual sealing operated from the inside, which seems to be “unaligned” with such a high degree of prefabrication.

Fig. 11 Façade installation process for the Nexity Ywood «L’Ensoleillée II» building in Aix-en-Provence (source: ©Nexity, Yann Bouvier)

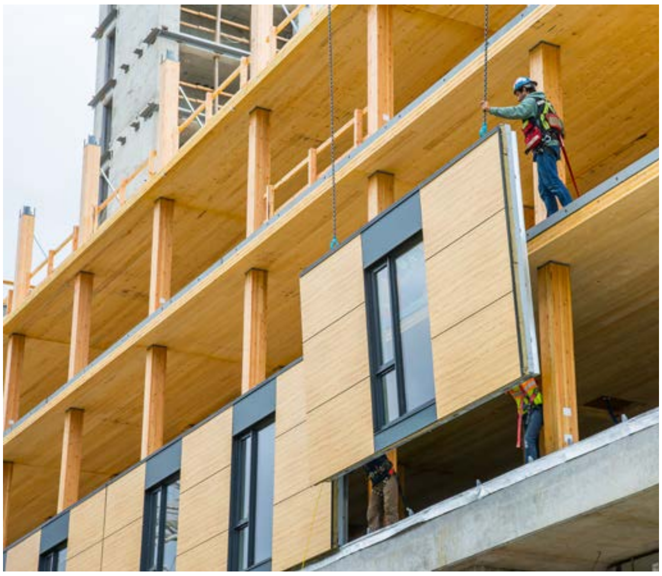

Fig. 12 Brock Commons fully prefabricated envelope installation phase (source: www.naturallywood.com)

Table 2: New construction case studies comparison. Prefabrication level is rated 1, 2 or 3 stars (*), for lower to higher prefabrication degree.

Case study ID	Height	Fixed scaffolding	Prefabrication level
HOLZ 8	8 storeys	Yes – lifting crane + scaffolding	*** cladding and windows installed offsite, interfaces completed onsite
LCT ONE	8 storeys	Yes – lifting crane + scaffolding	** windows installed off-site, cladding and interfaces completed on site
YWOOD BUSINESS	3 storeys	Yes – lifting crane + platform + corner scaffolding	*** cladding and windows installed offsite, interfaces completed onsite
BROCK COMMONS	18 storeys	No – lifting crane only	*** fully offsite finished panels installed onsite

4 Results discussion and conclusions

For the presented case study buildings in section 3.1, the average cost for square meter of renovated façade is in the range of 400-900 €. Of course, local construction market differences need to be taken into account, as we estimated that they may affect the total cost of works up to 20 %. However, a simple comparison with the result of the IEA ECBCS Annex 50: Prefab Systems for Low Energy/High Comfort Building Renewal research back in 2010 concluded a renovation cost equal to approx. 1000 €/m^2 of façade (International Energy Agency 2012), and highlights that the increasing interest and design effort in the direction of prefabricated systems for façade renovation are working in *favour* of cost reduction.

Current limitations to the adoption of prefabricated façade systems for building retrofitting at a larger scale are mainly ascribed to the higher cost with respect to non-prefabricated renovation systems, due to:

- Longer lead-time, with the necessity for more coordinated R&D before projects even begin to establish the capacity to deliver new products on time and at a guaranteed cost'
- More intense design effort with respect to traditional construction sites, due to the difficulty in adapting a high degree of prefabrication to the variability of geometry in existing buildings (i.e. construction tolerances);
- Lack of appropriate production infrastructures for the assembly of prefabricated panels. This reduces production speed, increasing costs, and capital expenditure required to procure such a capacity;
- Use of more advanced technological solutions with respect to traditional energy performance renovations, such as: integration of renewable energy sources (e.g. photovoltaic modules, solar thermal collectors); integration of HVAC systems. These components are costly with respect to a passive envelope solution, but the added value to the building in terms of comfort and performance deserves consideration (Jakob 2006).

In the case of envelope prefabrication for the timber high-rises, as seen in section 3.2, the state-of-the-art analysis shows how the design efforts carried out so far have not managed to solve the “prefabricated joint dilemma” yet. In fact, despite varying levels of façade panel prefabrication spanning from medium to high, which means including all functional layers and required components to ensure envelope correct function, junctions still require manual work to be performed on-site in order to guarantee air and water tightness. The root cause of these unsolved issues can be ascribed to the variety and complexity of multi-layer envelope systems, particularly in terms of number of parts and their reciprocal interrelation. In particular, main criticalities are:

- The gap along the production value chain in terms of design methods, such as Design for Manufacturing and Assembly (DfMA). To date, the manufacturing of opaque multi-layer envelope systems requires a much higher number of assembly operations when compared to unitized glass facades;
- The lack of coordination among suppliers to integrate different construction methods, optimise the use of materials and connection systems (e.g. screws, nails, rivets, glue) and develop new organic solutions in accordance with specific product requirements.

Further research effort in the future will focus on highlighting the extra-costs related to prefabrication, both in terms of design and construction, to determine which steps of the value chain are more likely to produce savings in the overall process. In addition, a point should be made on quantifying the productivity increases that can be targeted through the adoption of automated production lines. With respect to new construction, further research steps will also include the design of construction site-ready solutions, which allow for complete installation without the need of manual intervention after panel mounting.

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