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Prefabricated wood elements for sustainable renovation of residential building façades

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Abstract

Prefabricated elements to provide environmentally friendly, energy- and cost-efficient solutions for the building envelope have been studied. The newly developed element system has a high level of flexibility since it is possible to adjust the length of the connection rods according to the building's energy requirements and it can be mounted on timber, concrete and brick structures. Adjustability to different types of buildings structures, materials, tolerances, geometries and energy requirements makes it very applicable and efficient.

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Keywords: renovation, prefabricated wood element, building envelopes, façade renovation, energy efficiency

1. Introduction

There is a major need for cost-effective renovation of buildings in Europe because of the increasing age of the building stock, and a need for energy-efficient improvements due to European regulations intended to lower energy consumption and improve the environment. With a façade renovation, improvements can be made in energy savings in both the winter heating season and the summer cooling season, including better airtightness and reduction of drafts, especially in older buildings erected before the energy crises. At the same time, there might be a desire to

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change windows, improve the aesthetics of the exterior or to expand or extend the height of the building. This affects the architecture, and thus changes to regulation plans, building and fire regulations, *etc*. might have to be considered.

A façade renovation affects the performance of external walls in terms not only of energy performance and life-cycle cost but also building performance, physical behavior, durability and aesthetic appearance. Buildings in need of renovation have been built in different eras with different cultural-historical aspects, with different technologies and materials, and the local climates give rise to varying renovation needs. Economic conditions, ownership of the estates, building regulations and construction methods differ between countries. That makes it difficult to develop a single system for prefabricated renovation. In spite of that, many joint European renovation research projects have been trying to find an optimal solution for renovation; for instance, TES Energy Façade, Smart TES, Retrokit and SUSREF. [1] [2] [3] [4]

Tes EnergyFacade was a WoodWisdom-Net project with the goal of developing a facade renovation method for Europe based on prefabricated wood elements to improve energy efficiency. Smart TES focused on modernization of the building envelope and on developing and refining results from TES EnergyFacade. The aim of EASEE (Envelope Approach to Improve Sustainability and Energy Efficiency in existing multi-story multi-owner residential buildings) was to introduce innovative prefabricated solutions with insulation and good aesthetics [5]. MeeFS [6] (Multifunctional Energy Efficient Façade Systems for buildings retrofitting) is intended to develop, evaluate and demonstrate a multifunctional façade system. E2ReBuild, an EU FP7 project, had as its vision to transform the building sector from on-site building to an innovative, high-tech and energy-efficient industrial sector, working for an industrial building process [7].

Renobuild (Sustainable renovation of buildings using decision tools) has developed a methodology for evaluating different renovation options based on environmental, economic and social perspectives to help property owners to find the most optimal combinations of measures [8] [9]. The European SUSREF project developed concepts and technologies for refurbishment of building façades and external walls. The method is described in [10]. SQUARE was supported by European Programme Intelligent Energy Europe (IEE); the outcome was a Quality Assurance (QA) system – a tool for all building owners to enable retrofit and manage a large number of dwellings in a systematic and controlled way [11].

BEEM-UP (Building Energy Efficiency for Massive market Uptake) was a European FP7 project aiming to develop and demonstrate cost-effective, high-performance renovations of existing residential buildings and to reduce energy consumption [12]. BEEM-UP developed a methodology for evaluating optimal cost effectiveness as well as technical follow-up and tenant viewpoints.

To increase the possibility for export and import, there is a need to know the similarities and differences involved. Europe can benefit from the development of a common approach and a common view that facilitates joint innovation and export while making a greater degree of prefabrication simpler to achieve. Repeatability and reuse of the technology necessary for prefabrication are prerequisites in order to increase the attractiveness of residential blocks, revise energy efficiency and coordinate the refurbishing of the houses so that façades and buildings can be renovated in larger entities consisting of several houses.

The aim in a joint Nordic project is to develop a concept for industrial prefabricated insulated elements of wood for renovation and upgrading of building envelopes for residential buildings. The project started in 2014 and has participants from Sweden, Finland and Norway.

In this article, a newly developed façade element system has been compared with traditional façade renovation solutions and evaluated on two buildings, “Skiftesgatan” in Sweden and “Grindstugan” in Finland. Especially technical areas have been investigated and compared, such as adaptation to existing building and connections to underlying material, roof and base. The hypothesis is that industrial prefabricated elements make the renovation faster and with fewer disturbances to the people living in the building, and therefore mounting and transport have also been discussed. The idea with this research project is to evaluate and prefabricate solutions in order to reduce moisture exposure on site and to rationalize the construction process. We assume that a fast installation process and a short period of disturbance to the tenants are advantages of a prefab solution. Most important for the quality of the element product is, of course, the indoor production in dry conditions.

For a sustainable solution, wood-based elements were chosen, as they are environmentally friendly, renewable and CO2-neutral materials. A business model and the energy analyses are presented in two separate papers, and this paper presents the technical features of the elements and compares them with each other.

2. Methods of façade renovation

Typical reasons for renovation of a façade are to improve energy performance and airtightness and the need for a ”face-lift” due to deterioration and carbonation of a concrete façade. Depending on the cause and extent of deterioration and the type of building, different solutions can be chosen. Rather often, detail drawings and other important information about the building are missing for diagnosis of the building. To be able to determine the status of a wall segment, geometrical data and topography of the surface, different technologies are used such as photos, hand measuring, laser scanning and tacheometry. Other investigations that might be necessary to confirm status can be thermographic measurements, carbonization tests on concrete, microbial analysis, asbestos decontamination, *etc*.

To relate to reality, two houses were used for theoretical studies to compare renovation cases, and there was an inventory of housing stock in need of renovation in northern Sweden and Finland. In general, the building processes are similar in the Nordic countries, but there are differences and variations between each country. There are differences regarding typical roof connections, fire regulations and energy efficiency in Finland, Sweden and Norway. The design process also differs somewhat. The ownership of the building and the way apartments are rented affect the decision to renovate.

A questionnaire survey of customer attitudes to renovation was conducted in Sweden, Norway and Finland by email, with additional discussions with estate owners, builders, manufacturers and architects [13].

2.1 On-site renovation

A common way to renovate façades is to use a contractor on site that removes the outer layers of old façades and builds the new ones on site. The typical case is an organization where the house owner procures and manages the design process, but the site supervision is managed by a contractor. It is seldom that a contractor offers full service including design and construction work. The building process on site is normally managed by the contractor. The construction is exposed to the weather during construction, and there is risk for moisture damages. The basic and most common façade renovation method seems to be plaster on insulation. It is currently the most cost efficient method but, of course, comes with certain disadvantages, including moisture risk.

2.2 Prefabricated conventional large-element solutions

Prefabricated wood elements are made in advance in the factory according to the assembly-line method. The construction of the wooden elements is often the same as traditionally constructed walls. Common wood elements are formed as far as possible with complete insulation, sheathing on the inside and finished façade on the outside in order to reduce assembly time. When the wood elements are built indoors in a factory, that also reduces problems with building moisture and weather influences. The wood elements are completely finished with the surface layer, and the insulation must be protected from moisture during construction to minimize the occurrence of future moisture problems.

2.3 New element system

In this project, a new modular element system has been developed for renovation of façades. The elements are smaller than conventional prefab wood elements, consisting of laminated wood panels (solid wood) interconnected using wooden rods (see chapter 4). The production will be more automated than conventional prefabricated elements.

3. Inventory and case studies

3.1. Refurbishment and the customer view

A survey study of attitudes toward refurbishing in Sweden, Finland and Norway was conducted. The major findings where that people wanted an attractive environment and housing blocks. The constructions built in the sixties or the seventies generally have exteriors that have suffered deterioration and are in general not well kept up. One main aspect of the survey is that the costs must stay within limits. Selection of materials and sustainability did not score as high, but attractiveness and tidiness were of rather high priority. The use of wood and prefabricated elements will probably change the architecture, and especially if the original façade is not wood, the refurbishment and renewal of the façade will change the exterior architecture considerably. The survey also analyzed the potential obstacles to be found in master plans, but concluded that the master plans normally do not have any definite rules that make a change of the exterior impossible. From a technical point of view, the main aspects from a customer perspective are that:

- the solution is well thought through and has a positive impact on both the architecture and the inside living conditions
- thought is given to the unique construction of the house so the life span is not shortened
- the system has well thought-out solutions for easy retrofitting of, for example, awnings
- the system improves the insulation in order to decrease energy usage and sound transmission
- the system has a short construction time and has long-lasting materials
- the solution has a low cost and a long time between re-investments

A preparatory investigation has been conducted before, regarding studies of methods for the investigation of the existing structures [14], alongside literature reviews of previous research on this subject.

3.2. Case studies

Two buildings, one in Sweden and one in Finland, were used for theoretical studies to examine and compare renovation cases (see Fig. 1).

a)

b)

Fig. 1. (a) Skiftesgatan, Skellefteå, Sweden.; (b) Grindstugan, Vörå, Finland

Skiftesgatan

Skellefteå is a city located in the northeastern part of Sweden. Skiftesgatan is public housing with several similar buildings nearby. It was used as a referential case, with the intention to test a prefab solution on a similar building. Skiftesgatan (see Fig 1a) was renovated on site by a local contractor and an all-in contract with all work on site. The renovation started in 2015. The renovation was done to improve airtightness and minimize drafts in the houses built between 1972 and 1976. The exterior needed a ”face-lift” due to deterioration. The renovation was to be done without changing the eaves and roof, and therefore the added insulation was only 50 mm. Construction drawings were missing.

The all-in contract included the following conditions: The contractor was responsible for the entire project, which included additional insulation and new façades, replacement of all windows and exterior doors as well as window and door joinery. The tenants would remain during the entire construction period, and the work should be planned and conducted to minimize disturbance. The contractor was to provide all necessary information to tenants. Wall: On existing studs, new thermal insulation, t = 50 mm, battens 28 x 70 mm, s600 and vertical boarding 23 x 45/23 x 95 or tongued and grooved boards 22 x 120 mm. The panels were to be made with full lengths without joints. Cladding primed in factory with oil-based paint in the same color as the existing building and two layers of on site painting with acrylic paint. Windows, wood-aluminum construction, triple insulating glass with R-value ≤ 1.2 (W/m2K). Ventilator Biobe Audiovent 60.

Grindstugan

Vörå is located on the west coast of Finland. The need for façade renovation and insulation was investigated for Grindstugan (see Fig 1b) and used as a case for theoretical studies. Grindstugan is two-story dwelling house that was built in the beginning of the 1970s and consists of 18 flats in total. Load-bearing partition walls and joists are of poured-in-place concrete. The exterior walls of the long sides have a wooden framework with fiberboard and wood panels as façade material while the end walls have a brick façade. Airing balconies are found at each of the three staircases on the front, and balconies belonging to the flats are found on the back of the building. No structural drawings were available. Only main drawings could be found. A 10- x 10-cm piece of the façade was removed from one of the building's long sides in order to investigate the wall structure. The vapor barrier was left untouched. From the outside in, the construction consisted of 21-mm façade panel, 12-mm air gap, 7-mm fiberboard, 32-mm air gap, 3-mm fiberboard, 100-mm frame + mineral wool, 13-mm gypsum board + vapor barrier. A laboratory investigation of the fiberboards concluded that they consisted of asbestos cement sheeting. The double layers of fiberboard are probably a result of an earlier façade renovation. The end walls have a brick façade with bricks sized 285 x 85 x 85 mm, followed by 100-mm insulation and 160-mm concrete. Since the apartment house was built in the 1970s, it is assumed that there is no air gap between the brick and the insulation behind it.

4. Technical solutions

The aim was to investigate the possibility of renovating a house with prefabricated wood elements and to highlight the various possibilities and problems that arise with this type of method compared to the houses in Fig. 1.

Skiftesgatan was renovated with only 50 mm additional insulation, which from energy-conservation viewpoint is little, but the purpose of reducing drafts in the house was achieved. A simple connection to the roof was crucial because no changes would be carried out on the roof, thus reducing costs. The renovation was carried out in small steps and implemented in a "safe" way, but with a long presence and disturbance for residents in the area. The Grindstugan renovation has not yet been carried out and is expected to be completed during 2017. Literature studies, inspection of the building, co-operation with local manufacturers and a wood-based building system have been elaborated for Grindstugan with appurtenant detail drawings of the building connections [14].

4.1 Prefabricated conventional large element

4.1.1 Size of façade elements

The height of the wood elements is adapted to the height of a story and the length to the distance between concrete partition walls (4–8 m). The new façade is made up of 18-mm reinforcing sheets of plywood or OSB (Oriented Strand Board), 100-mm insulation + 48- x 98-mm vertical framing studs attached to the reinforcing sheet at 600 mm center to center, 25-mm non-flammable windbreak plate, 32-mm ventilation air gap + 32-mm wood studs, and a façade panel of the customer's choice. The total thickness will be approximately 200 mm. The distance of 600 mm between studs corresponds to a wooden thermal bridge share of at least 10% within the insulation layer. Horizontal wood elements are preferred over vertical elements because they allow for easier loading, transport and installation.

4.1.2 Connections to underlying material

The attachment of wood elements to underlying material of concrete structures and wood studs along the long sides of the building was studied. There is some uncertainty about how much of the existing façade will have to be removed in order to locate attachment points. After demolition, it is likely that the wall will be uneven, and therefore a mesh of mounting battens will be built as a rest surface to attach the wood elements to.

For use of elements on varying types of existing walls, the size, attachment and tolerances of the elements are important. If the existing façade consists of traditional concrete elements in good condition, it is possible to attach mounting battens and install new elements directly to the old façade with no need for demolition. This requires that the existing façade has not been subjected to moisture damage. If the old façade contains a ventilated air gap, the outer shell will have to be removed down to the windbreak plate. Even in this situation, the existing façade's condition should be inspected, especially with regard to mold growth. If that is discovered, the material should be replaced with sound material before attachment of mounting battens. After additional insulation, the existing wall will exist in a warmer and dryer environment.

The façade's mounting battens are arranged horizontally level with the joists and vertically in line with load-bearing partition walls. The battens will form a grid that is adjusted to squares during attachment. The mounting battens are wedged and fastened to the underlying frame with long screws or with strike anchors fitted with threaded plugs. Washers and bolts are countersunk into the battens. The plugs are cut off after it has been determined that the battens form a flat surface. The principle is that all depth adjustments are done in this phase. The gap between the old wall and the new element must be filled with approximately 50mm of insulation, preferably mounted on the new element in the prefabrication process. Wood screws are used to install the elements on the mounting battens that have been attached to the underlying façade. An airtightness of approx. 1 m3/(h m^2) (SFS-EN 13829 2000, B-standard) [15] is possible to achieve in the erection of new buildings with large elements, with improved airtightness.

Installation of wood elements is done from the plinth with wedges (see Fig 2a). The same principle is applied higher up as well. Joint thickness and adjustment room are attained with the use of wedges. The plinth is made as a sheath element of pre-insulated concrete. The sheath elements rest on steel brackets that are fixed to the existing plinth with wedge, strike or chemical anchors. On-site work is needed for connections to roof structures and balconies, and presumably also for window connections. Fig 2b shows a detail of the element and its mounting to the load bearing structures at the intermediate floor. Layers 1–3 are the existing wall (panels and air gap removed), and layer 4 is an adjustment layer, while layers 5–7a constitute the new element (potentially including layers 8 and 9a). There is a horizontal fire stop at the height of the intermediate floor to prevent the spread of fire through the air gap. To prevent fire spreading, a cavity-free construction or usage of fire stop is necessary [16].

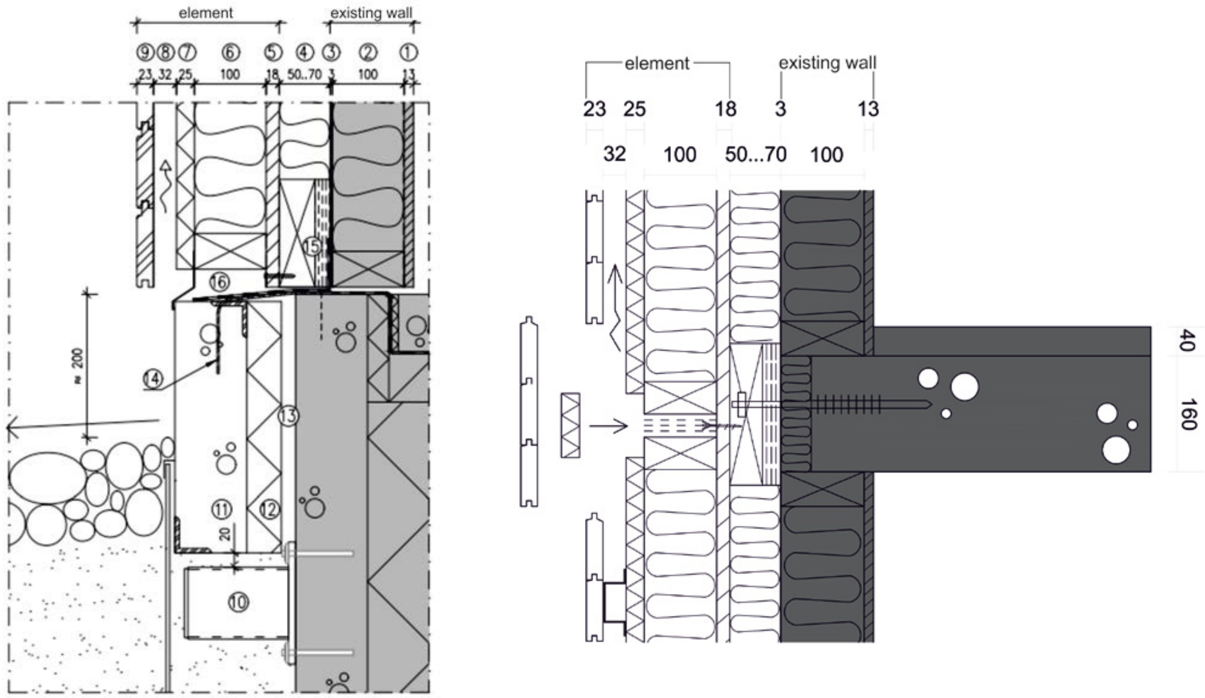

Fig 2. a) Connection to the plinth b) Vertical element at intermediate floor [14].

4.2 New modular element system

In this project, a new system of small, modular prefabricated wood elements called "modular wall system" has been developed for renovation of façades (see Fig. 3). The aim is to achieve more flexible solutions than those already in existence.

Fig 3 Photo of the modular wall system patented, Termowood As; EP1963593, NO 323561.

Vertical cross-section showing the system structure with wood and concrete (see Fig. 4).

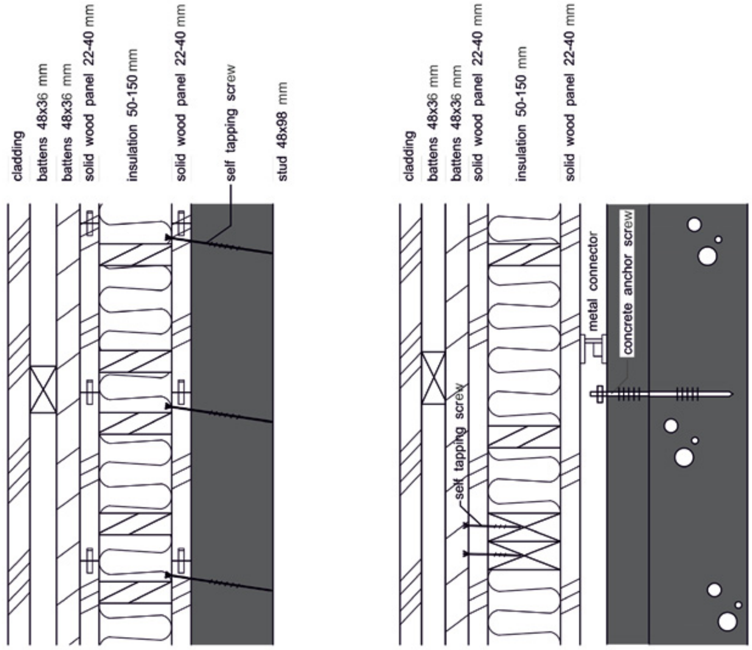

Fig 4. The patented system solution depending on material in the building being refurbished. A) Vertical cross-section with wood b) Vertical cross-section with concrete

The insulation is placed between the outer and inner element structures. The product is available with 5–25 cm of insulation, depending on the customer's requirements and need for upgrading of insulation in the building. The product will be delivered in two versions, as load bearing wall elements and as nonstructural elements used for renovation projects as presented here.

The modular element consists of two outer parallel-aligned multilayer solid wood panels with insulation in between. The outer layers are connected to each other by wooden rods. Elements are produced in segments with a size range of 20 x (9.4–23.0) x (240–500) cm (w x d x l), a thickness (t) of 2.2–4.0 cm of the multilayer solid wood panels and a connection rod length of 5–15 cm. An asymmetrical element structure, such as using an inner panel with t = 40 mm and an outer panel of t = 22 mm, can be adjusted to improve the segment's load carrying capacity and insulation. Wall elements can be combined in various sizes by assembling segments together horizontally or vertically using a tongue and groove connection (see detail in Fig 4a), with a backing rod in the joints to ensure airtightness.

4.2.1 Size of façade elements

Maximum size of wall elements is the transport limitation set by road authorities in each Nordic country and the internal dimensions of a trailer. In Norway, that is, respectively, 3.25 m in width and 15.0 m in length and 2.40 m in width and 13.5 m in length. The flexibility in terms of mixture of element sizes and the independence of outer ventilated façade material enables the system to adjust to different building geometries, tolerances and energy requirements and to adapt to different façade expressions.

The sizes of the elements have an impact on efficiency in production and assembly on site as well as the ability to adjust the elements to an existing building.

Tolerances for measurement of existing structures, execution of the prefabricated elements and on-site production should conform to tolerance class 2 (Norwegian standard for execution of timber structures prNS 3516 [17]. The modular element system has one advantage compared with previously developed large-element systems, such as smartTES: it combines prefabrication advantages of larger elements and on-site work using modular elements, which makes it more easily adjustable to existing structures as the work on site progresses.

4. 2.2 Wall thickness and insulation

Based on minimum thickness of the outer layers in the flexible element of 22 mm multilayer solid wood panels and an insulation thickness of 50 mm, the minimum thickness of the modular rehab wall element is 94 mm. Maximum thickness is set to 230 mm with 40-mm outer multilayer solid wood panels and 150 mm of insulation.

Since it is possible to adjust the length of the connection rods according to the building's energy requirements, the system has a high level of flexibility. Moreover, due to the hollow structure of the all segments, the panels can be prefabricated with blown-in insulation, insulation mats or both, depending on what is more efficient and economical for the individual project. Insulation can also be blown into the wall elements on site and mats used as complementary insulation. The thermal conductivity (lambda value) of the insulation material varies from $\lambda d=33$ mW/mK (Stone wool mats) to $\lambda d=37$ mW/mK (wood fiber blown in).

Two types of construction solutions have been designed for applying the modular system to concrete, brick or light-frame walls. For both brick and concrete walls, the system is built with a cavity layer of minimum 48-mm space between the existing wall structure and the modular wall system. The cavity layer and the wooden panel in the refurbishment wall system can be used to dry out and stabilize the level of humidity in the existing wall surface. Vented fire barriers are built in the cavities to prevent fire from spreading vertically.

4.2.3 Moisture risk analysis and solutions

Simulation of moisture cases in six different wall constructions of the modular system was done with WUFI program [18]. First, the existing wall structure was simulated for 20 years with the weather conditions of Umeå in Sweden, weather conditions from the WUFI program. Umeå is a city close to the houses in Sweden and Finland. The result o this simulation was used as an initial condition for the following simulation of the element. Both symmetrical and asymmetrical constructions of the modular wall system, with 22-mm and 40-mm thick solid wood panels, were simulated with 50-mm and 150-mm insulation in between. The results from the simulations show no sign of problems with condensation.

In terms of thermal bridges, the modular system has, with its connection rods in wood (d=30 mm and a raster spacing of 160 mm x 500 mm), a thermal bridge area of approximately 212 cm^2/m^2wall, unlike a standard light frame wall with 48 x 98 mm studs c/c 600 mm spacing which has an area of 960 cm^2/m^2wall. The significantly lower thermal-bridge area in the modular wall system reduces the risk of condensation.

The airtightness and wind tightness of the refurbishment layer is ensured by using backing rods in the joints between segments of the modular system, sealing of joints between elements with adhesive tape and covering insulated intermediate gaps with a membrane. An air leakage test done according to standard NS-EN 13829 [19] at a multi-family house in Norway built with a modular wall system gave a result of 0,67 m^3/m^3h which fulfills the Norwegian building regulation airtightness demands of $\leqslant$ 1,0 m^3/m^3h for low energy class 1 according to test at building site Hurdal in June 2016.

4.2.4 Connections

For existing façades of brick or concrete, wooden battens are added to the load-carrying structure by using wall connectors or concrete anchor bolts and screws. These fastening systems are specially developed for fastening wooden members to brick or concrete. The purpose of the battens is to equalize for imperfections in the existing surface and to make it easier to attach the modular wall rehab element to the façade. Finally, the wall elements are mounted on the battens with self-tapping screws. On a light-frame wall, the refurbishment modular wall system is fastened directly to the load carrying studs without establishing any cavity space. In comparison, the depth of a light-frame system is not as adjustable because it depends more on the standard dimensions of the studs and insulation. For light-frame walls, the modular wall rehab element system is mounted directly onto the studs in the wall with self-tapping screws, given that the studs can carry the rehab element and the outer ventilated cladding.

In order to prevent vertical displacement in the modular rehab elements due to heavy cladding and long-term load effects, the tops of the rehab elements are connected to the ends of the roof trusses with metal purlin anchors. Metal brackets can also be mounted at the base of the wall to carry the vertical loads of the rehab elements. The ability to attach brackets to an existing building structure depends on its state and can be very challenging technically. Both the modular element system and the more traditional light-frame construction rehab solutions are designed for different load situations. A prerequisite is that the load-carrying structure in the existing façade can carry the self-load of the exterior refurbishment construction.

5 Production, logistics and installation

The modular system has from the start been focused simultaneously on both product development and production development with the aim of obtaining the optimum product within cost, and a chain of profitable production has been the goal. The main objective has been to design a system that can generate a profitable industry in the Nordic countries for production of renovation elements. In order to establish a competitive industry, it is necessary to have production facilities that produce at low-cost with reduction of workforce together with a logistics and on-site installation focusing on low-cost, high quality issues. Fig. 5 shows the simplified model of the system.

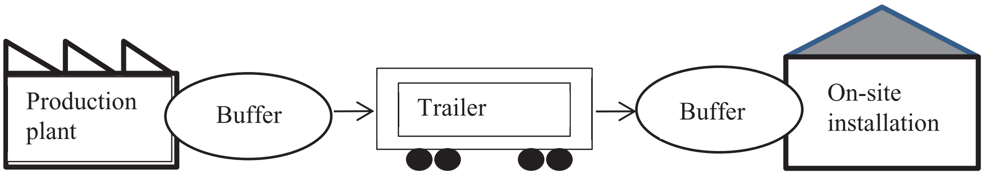

Fig. 5. Simplified picture of the logistics system

The production plant should be highly automated and focus on current and future challenges using a system that ensures efficiency and reduced costs. The logistics are going to need some buffering in the system to handle the variations on the site installations. In the design stage, the buffering is planned and reduced to a minimum so the real on-site installation development will influence the final production rate. A plant for production of modular units at full-scale has been shown to be able to produce 60 items per hour or 480 items per shift (250 m^2) with three workers. In a separate set-up that's been developed, individual elements can be assembled into larger elements at a speed of two items per minute (1 m^2). The adjustability to different types of building structures, materials, tolerances, geometries and energy requirements makes it very applicable and efficient.

The modular wall system has elements that are prefabricated in various sizes consisting of 200-mm wide segments, with a length up to 13.5 meters. After the prefabrication of elements, they are preferably loaded directly onto curtain trailers to ensure dry and safe transport to the building site or to a weather protected buffer area. In order to have a swift production on site, the elements are arranged in a set assembly order as much as possible. Rain protection covering during transport and storage at the building site is important to prevent excessive moisture from entering the modular wall system.

Installation on site is conducted in high speed, more or less continuous installation for moisture reduction, using a crane and with no need for scaffolding. This not only reduces moisture exposure; it also allows the tenants to remain living in the apartments during renovation. The system can be assembled horizontally or vertically. Cladding can be mounted during prefabrication of the elements and completed on the building site. In the case of horizontally-oriented segments and elements, battens are attached to the existing façade vertically. A butterfly table can be a flexible and efficient tool for assembly of the wall segments, inserting the backing rod manually in the tongue and groove connection between the segments and mounting a ventilated cladding. Prefabricating the elements with battens for the ventilated cladding will connect the segments and stiffen large-size elements. To make the mounting of the prefabricated elements efficient, metal connectors can be installed on the back side of the elements and on the existing façade. Alternatively, two and two elements are produced and fastened to battens, which are mounted on existing façade using self-tapping screws. A major aspect in choosing how to streamline the installation is the requirement to stay within tolerances of less than ±20 millimeters.

6. Comparison of element systems

Our conclusion is that there are similar advantages and disadvantages with wood-based prefab element structures in an adaptation to existing buildings and connections to underlying material, roof and base for both types of elements. We found that a fast installation process and a short period of disturbance to the tenants are advantages of a prefab solution. Indoor production in dry conditions is, of course, important for the quality of the element product, and as little work as possible should be left to do at the site. This is a major advantage compared to current practices with almost all work done on site.

The choice of system will not significantly affect the aesthetic aspects and performance of the facade. Both systems can carry different cladding materials and offer the same finish. Modular elements must be assembled into larger units if one wants to avoid installation of exterior panels on site.

In general, we assume that both large-element installations and modular element projects will face similar problems regarding connections to roof and base, as well as to windows. All systems also face the need for an insulation layer between the existing wall and the new element structure in order to avoid horizontal or vertical convection inside the wall. We also assume that both element types require some degree of removal of outer wall structures, at least to the extent of uncovering the air barrier. All these measures require work on site in any case.

The major difference in energy efficiency stems from the amount of thermal bridges, where the modular elements have a lower share of thermal bridges. Regarding airtightness, it is mostly dependent on the quality of the work, and thus we assume that both element types can achieve the same level of airtightness. The structure of these modular elements with few thermal bridges make them less sensitive to moisture, which might be a problem when adding insulation and the temperature inside the wall structure rises.

The advantages of the modular elements are found in the simpler installation process and the fact that the installation can be done with smaller screws more frequently distributed, which is better tolerated on a weaker structure. In a renovation project, it can be difficult to accurately locate the load-bearing structures behind the exterior wall, as detailed drawings often are missing and the walls have not necessarily been built exactly according to the extant drawings. Both larger and smaller modular elements are easy to install on a planar structure, but smaller elements, of course, tolerate minor unevenness in structures.

The use of modular elements allows for a systematic removal and installation process, which can better adjust to bad weather conditions. Due to the smaller size, the installation process with the modular elements is easier to manage, which is advantageous, as renovation projects tend to have limited access routes and little space for cranes and lifts.

7. Conclusion

The designs of buildings vary and must be taken into account in any renovation project. Preliminary investigation of a building's status is an important part of planning so that possible critical points can be discovered and considered in the initial phase. Since there are deviations and irregularities on the facades, wood elements must be designed so that adjustability is possible during installation.

The structural parts of the new elements are made of wood, with various options for surface materials. The elements can be made as small elements or for full wall height, depending on the requirements. The construction of the wood panel makes it possible to mount on timber, concrete and brick structures. It is possible to adjust the length of the connection rods; therefore, the modular system has a high level of flexibility. Moreover, the elements can be efficiently prefabricated with blown-in insulation, insulation mats or both, depending on what is most efficient and economical for the individual project. Since it is possible to mount it either as single segments, small elements, large elements or a mixture of all three sizes, the system is flexible and efficient in terms of adjusting it to the geometry, energy requirements and tolerances of the existing building structure.

One research question arising from this study is how to standardize connections to a minimum number of solutions that are easy to manage. The advantages with modular elements are to be found in the advantages of mass production indoors and a repeatable application on standard types of housing dwellings. The number of typical facades that are in need of renovation is estimated to be quite large.

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