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10.1 Introduction

It is estimated that 85%–95% of the buildings that exist today will still be standing in 2050 (European Commission, 2020), accounting for almost 40% of energy consumption in the European Union (EU) (Tsemekidi Tzeiranaki et al., 2020). The role of the existing building stock is instrumental in the energy transition and the goals for carbon neutrality of the built environment (Filippidou & Jimenez Navarro, 2019). Renovation is an integral part of the building's life, as the different components reach the end of their service life (Brand, 1994). Every year, 11% of the EU existing building stock undergoes some level of renovation. However, renovation works that address the building's energy performance are at a rate as low as 1%, with a deep renovation that achieves energy reduction over 60% being at 0.2% (European Commission, 2020).

The upgrade of the existing buildings stock can result in significant energy savings, improved health and comfort of the occupants, elimination of fuel poverty and job creation (BPIE, 2011). Nevertheless, to tackle this potential, both the number of renovated buildings and resulting energy savings need to increase (Artola, Rademaekers, Williams, & Yearwood, 2016). The annual rate of renovated buildings to the total building stock varies from 0.4% to 1.2% in the different European Union Member States (European Commission, 2020). This rate will need to double to reach the EU's energy efficiency and climate objectives for no greenhouse gases net emissions in 2050 (European Commission, 2019).

An effective renovation plan must significantly improve the current energy performance toward a zero-energy level. Interventions that reduce the building's energy demand and generated power are essential to attain this goal. Nevertheless, most improvements in residential buildings currently consist of basic maintenance and shallow renovation. Broader or deeper energy renovation measures that result in higher energy savings are required (Filippidou, Nieboer, & Visscher, 2016).

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Several studies, such as BPIE (2011), Meijer, Straub, and Mlecnik (2018), have been looking at barriers to renovation implementation and upscaling. Next to financial, institutional and regulatory barriers, there are also informational barriers related to the lack of common direction among the main stakeholders and the lack of overview of which building types and renovation activities to prioritize (Jensen, Maslesa, Berg, & Thuesen, 2018).

Particularly when tackling deep retrofitting actions, higher complexity and costs are incurred compared to lower impact energy retrofitting solutions. Large-scale building renovation is still considered a difficult task (Filippidou & Jimenez Navarro, 2019). This perception can be attributed to the large number of retrofitted components, their interconnection and the integration of renewable energy sources (Avesani et al., 2020). Moreover, renovation projects are complex to carry out because of the many actors involved (D'Oca et al., 2018) and high risks for contractors due to the lack of lean methods and risk-sharing models (Bystedt et al., 2016).

Industrialization can trigger a virtuous circle between higher demand for energy-efficiency renovation and falling costs for smarter and more sustainable products (European Commission, 2020). From this perspective, industrializing the renovation process helps to overcome some of the financial and stakeholders' issues. It can bring the costs down, utilizing the large numbers of the buildings to be renovated to lead to economies of scale. Additionally, it offers opportunities for end users to benefit from high-quality, affordable products and institutional real estate owners to benefit from affordable customization. Industrialization is an effective strategy for improving the construction industry's productivity (Hong, Shen, Mao, Li, & Li, 2016), which is an important consideration given the enormous renovation task at an European level (BPIE, 2013). Furthermore, prefabrication of the retrofitting components can achieve high-performance results while minimizing on-site construction time (IEA Annex 50, 2012).

Industrialization is not a new concept in the building industry. The idea of industrialized building systems has been developed since the interwar years and the Modern movement (Moe & Smith, 2012). In recent years, prefabrication in the whole building market is currently undergoing significant growth (Tumminia et al., 2018). However, in renovation, the holistic application of prefabricated modules is often only used in subsidized demonstration cases (BPIE, 2016) and not experience a high market uptake (Bystedt et al., 2016).

Considering the need to upscale renovation of the building stock and the potential of industrialized renovation to achieve that this chapter discusses current practices of industrializing the building envelope's renovation. First, we determine the role of the building envelope as an integral part of deep renovation strategies. Subsequently, the definitions and application of industrialized techniques in the design and construction of renovation are investigated, particularly regarding the renovation process and design concepts. Finally, the chapter gives an outlook on critical aspects for the future of industrialized building envelope renovation.

10.2 The importance of the building envelope for deep renovation

Before discussing industrialized renovation in more detail, we need to establish a common vocabulary about the type of interventions this building activity comprises. Different terms, such as major renovation, deep renovation, refurbishment and sustainable renovation, can be encountered. Those terms have in common that they deal with an existing building, and they need to consider the existing condition, function, users, architectural characteristics and performance (Jensen et al., 2018).

The depth of renovation is defined by the level of savings on energy, specifying as deep such renovations that achieve energy savings of 60%−90% (BPIE, 2011; European Commission, 2019/786). Deep renovation, in particular, has the potential to be the preferred solution from an ecological and economic point of view. As opposed to deep renovation, superficial renovations significantly increase the risk to miss the climate targets of savings in energy and CO_2 emissions to remain untapped (Hermelink & Müller, 2011). Despite having a higher initial investment, deep renovation also generates higher energy savings (BPIE, 2011). As a result, deep renovation, toward zero-energy standards in existing buildings, is set as a priority in long-term renovation strategy (DIRECTIVE, 2018/844/EU).

Jensen et al. (2018) are using the term sustainable building renovation 'as the renovation of existing buildings that results in upgraded buildings, which are more sustainable in terms of environmental, social and economic aspects after the renovation than before− or at least in relation to two of these aspects'. Based on this definition, reducing energy consumption and the related CO_2 emissions of a building is considered part of a sustainable renovation. It improves its environmental impact while lowering the cost of energy use for the occupants.

In current practice, renovation is a term widely used to express a range of construction activities related to interventions onto existing buildings. They range from simple repairs and maintenance, restricted to replacement or repair of defective components, to adaptive conversion and reuse, which affect the load-bearing structure and interior layout. Giebeler et al. (2009) places renovation works close to maintenance and cosmetic repairs that do not add new components. On the other hand, refurbishment refers to defective or outdated parts, components or surfaces being repaired or replaced, with no major changes in the load-bearing structure (Giebeler et al., 2009). The upgrade of fire protection, acoustics and thermal performance can be achieved through the building's refurbishment. Additionally, during the refurbishment, buildings can be retrofitted with technologies for energy generation from renewable sources. Retrofits are defined as the strengthening, upgrading or fitting of extra equipment to a building once the building is completed (Gorse, Johnston, & Pritchard, 2012). In this sense, refurbishment and retrofits are very similar as activities, as they both address replacing and upgrading building components. For this chapter's discussion the term 'renovation' will be further used, as it is a term widely used in the building industry and policy documents. It is considered to encompass measures that refurbish or retrofit building components.

Regarding deep renovation in particular, which aims to save over 60% in energy demand, a combination of measures is needed. The renovation strategy should address different building components. Regarding technology to be used for sustainable and energy-efficiency building renovations, the amount and sophistication of building materials, technical installations or services has escalated over the past decade (Jensen et al., 2018). The primary interventions, as defined by Pacheco-Torgal et al. (2017), include the following:

- heating and cooling demand reduction, such as thermal insulation, multiple-pane windows and increase of airtightness;
- energy-efficient equipment and low energy technologies, such as thermal storage and heat recovery; and
- renewable energy supply using technologies, such as heat pumps, photovoltaic (PV) panels and solar collectors.

It is then clear that the building envelope is essential as it is the medium to apply those measures, combining both passive and active measures (Kilaire & Stacey, 2017; Konstantinou, 2014; Pacheco-Torgal et al., 2017). Not only can the building fabric prevent heat losses but also it can incorporate technologies such as PV panels and other building services. Moreover, the building envelope is a component with a shorter life span than the building structure (Brand, 1994). Retrofitting the building envelope to tackle physical signs of deterioration and upgrading its performance extends the building's life span.

Based on the previous definitions and type of interventions, the present chapter uses the term 'renovation' as a building activity that applies a combination of measures on an existing building, including the building envelope, with the aim, but not limited to, of improving energy efficiency.

10.3 Degrees of industrialized renovation

Industrialization in the context of building products refers to items produced in a repetitive process. Richard (2005) defined industrialization as 'catering a large market, by investing in technologies that simplify production and also reduce cost'. This principle commonly applies on a small scale, such as screws and standardized building products, such as bricks or doors.

The term *industrialized construction* is often used interchangeably with prefabricated construction; however, it is not strictly the same. Industrialization aims at simplifying the production process of complex goods using strategies and techniques that require an investment divided over a high production volume and, therefore, marginal per end product. Bricks, for example, are an industrial interpretation of adobe architecture. The fired modules are easier to transport and handle and more robust than earth. This optimization of the production process resulting in higher quality requires an investment, for example, for the acquisition of moulds and a kiln. Therefore it is essential to balance the upscaled production with the actual demand to justify the initial investment.

Under the umbrella of industrialization, five different degrees can be found (Richard, 2005). *Prefabrication* can be seen as a subset of industrialized construction. The other degrees are *mechanization, automation, robotics* and *reproduction*. The definition of those degrees does not imply a hierarchical classification but different type of activities. The first four degrees described in Table 10.1 are applied in practice separately or combined to build the industrial character of a production process. Reproduction is as an overarching degree that aims at maximizing replicability. The separate degrees can be seen as complementary, independently or building upon each other.

Particularly in building envelope renovation, the different industrialization degrees can be found in literature examples and case studies. The next table is an introduction to the different degrees of industrialization and some example activities.

In current renovation practices, mechanization and automation are increasingly applied. The degrees of industrialization are often combined to deliver the final result. Renovation as a part of state-of-the-art construction activity is already largely industrialized. However, the possibilities to expand the degree of industrialization in the renovation are important, particularly given the need to increase the depth and rate of renovation of the building stock. Thus industrialized renovation should aim at going beyond standard practices. Within this chapter's scope, we refer to industrialized renovation as the renovation that increases the energy efficiency of the existing building stock while aiming to maximize reproduction, through an effective combination of all degrees of industrialization, particularly with the application of prefabricated components.

10.4 Industrialized renovation process and state of the art

Industrialized renovation follows a similar process to other building renovation projects. This process includes the project requirements' definition, concept design, final strategy design, execution and, finally, the renovated building (Konstantinou, 2014). However, in the industrialized renovation, several steps in the decision-making and the design and engineering are specific to the degrees of industrialization, particularly regarding prefabrication, and reproduction. This section presents the process that relates to the industrialized renovation. Moreover, it elaborates on industrialized renovation design concepts, as illustrated in state-of-the-art examples.

10.4.1 Industrialized renovation process

Manufacturing and installation benefit from the industrialization of the renovation in terms of cost reduction, replicability and productivity. However, a large share of the effort to achieve a high level of reproduction occurs during the design and engineering of the components. The design is optimized and standardized, modularity

Table 10.1 Degrees of industrialization in renovation (Richard, 2005).

Degree of industrialization	**Description**	**Example of related activities in renovation**
Prefabrication	Building components or complete modules off-site (in the factory) before being transported to the site and become an integral part of the building	• Construction of façade units in the factory, with integrated components, such as windows and ventilation pipes • Retrofitting with sandwich panels, prefabricated in a factory • Retrofitting of building services with preassembled configurators
Mechanization	Machinery is employed to ease the work done with human intervention. This is already a widely adopted degree of industrialization	• Using CAD software to draw and communicate design • The use of hand tools, such as a hammer or a drill • Using a crane for heavy and large object lifting
Automation	Tooling completely takes over a repetitive production task without the need for a tool or workpiece adjustment by human intervention	• Optimization with the use of parametric design generation • Sheet metal forming in a press brake and automatic tool changing
Robotics	Tooling has the flexibility to perform diversified tasks without human intervention	• Scanning a renovation object with a drone • CAM tools, including a multiaxis milling machine or robotized bricklaying • Bricklaying with a robot arm
Reproduction	Simplified multiplication, with the use of the degrees of industrialization	• Inventory method for potential renovation objects on an urban scale using publicly available photographic data • Retrofit system that provides adaptability through a variable choice of highly efficient energy technologies and intelligent controls • Standardized interfaces applicable to varying modules for a prefabricated façade solution

Source: Adapted form Richard, R.-B. (2005). Industrialised building systems: Reproduction before automation and robotics. *Automation in Construction*, *14*(4), 442–451. https://doi.org/10.1016/j.autcon.2004.09.009.

can be introduced to customize the end product, and functional and material synergies are created. To this end the chapter looks into the renovation process and identifies the key aspects of industrialized renovation that influence the decisions and when they are considered.

In an effort to systematize and facilitate decision-making during the construction projects, different phases have been identified (Cooper et al., 2005; Klein, 2013; RIBA, 2020). The exact number of phases and subphases might vary in the different publications, but there is consensus on the main broad stages. The stages are the preproject, which defines the need for the project; the preconstruction, when an appropriate design solution is developed; construction, which implements the solution; and postconstruction, which aims at monitoring and maintenance of the project.

The renovation process, which researchers have also specified (Ferreira, Pinheiro, & Brito, 2013; Konstantinou, 2014; Ma, Cooper, Daly, & Ledo, 2012), is still a construction project and the phases mentioned earlier apply as well. However, since renovation is dealing with an existing building, the preproject phase includes the analysis and diagnostic of the building to define the intervention's scope. Moreover, the existing occupants that might continue to occupy during construction have an important role in the execution phase, for example, with regards to time planning. Industrialized renovation follows the same phases, but some subphases are specific or more essential compared to on-site renovation construction, particularly with regards to the existing building analysis, the renovation design and the components' production (Aldanondo et al., 2014). Fig. 10.1 shows an overview

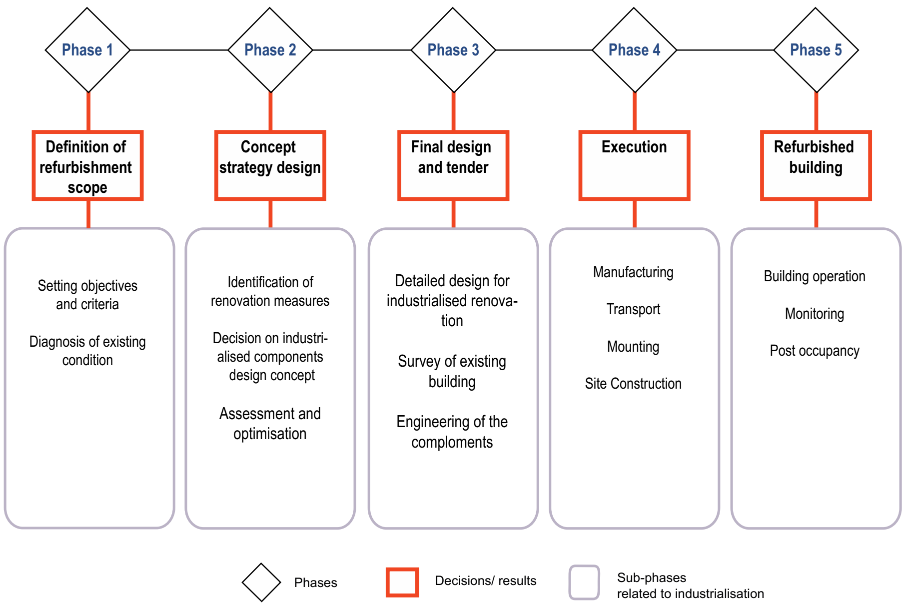


Figure 10.1 The renovation process, adapted from Konstantinou (2014), includes the subphases that are important for renovation industrialization.

of the renovation process phases, including the important activities for industrialized renovation.

The decision to develop an industrialized renovation concept determines the concept design and the measures' specifications. There are several designs and construction concepts, as will be discussed in Section 10.4.2. The design of an industrialized renovation concept does not start from scratch, as is often the case in the on-site renovation. Once the system has been developed, reproduction for the different projects is possible to a large extend. The design focuses on adapting the industrialized concept to the project specifics, geometry and energy performance objective. The design's replicability, which is defined in the concept design phase, facilitates the standardization of construction details and the supply chain, which occurs in the final design and tender phase. A significant step of the industrialized construction is the detailed survey of the existing building.

Based on the experience of the research project EASEE ('Envelope Approach to improve Sustainability and Energy efficiency in Existing buildings'), where insulating prefabricated panels, for a total of 28 different typologies and with different textures were applied, Brumana et al. (2016) have organized the renovation process into the following steps:

- laser scanning technologies and thermographic survey campaign of the existing building's envelope, to identify nonhomogeneous parts of the building structure and support the design and the installation of the prefabricated panels,
- use of building information modelling (BIM) tools in the design of the panels and the anchoring systems, toward the automation in the installation of the elements and the energy performance evaluation over time,
- architectural and executive design of the renovation and the manufacturing of the prefabricated panels,
- installation to the existing building facades utilizing steel profiles and realization of the finishing works and
- monitoring campaign before and after the renovation, to evaluate thermal performance.

Next to the building dimensions, the components' size is determined by the product design, manufacturing and transportation capacity and mounting method. There can be certain limitations in terms of size; typically, the factory can provide a maximum width, height and panel thickness according to the equipment and facilities dimensions (Fig. 10.2) and the vehicles that will transfer the panels to the building site.

Finally, panels can be hung directly onto the façade using brackets if the façade has the load-bearing capabilities. Otherwise, a concrete block is added at the bottom of the lowest panel onto the façade. The panels are stacked on top of each other and the load is transferred through them. The panels still need support from the façade for wind and rain load, however. Different anchoring systems are possible, such as the examples in Fig. 10.3.

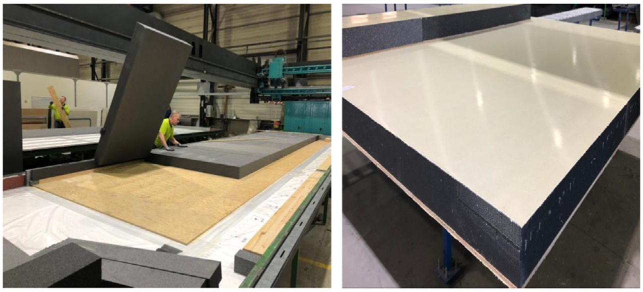


Figure 10.2 The manufacturing process of the sandwich panel in the Rc panels factory, Overijssel, the Netherlands. The panel's max length is determined to be 13 m (Rc Panels, 2021). *Source:* Nunez, R.

Figure 10.3 (A) The panels are connected to wooden posts, attached to the existing structure with steel U profiles. (B) Anchors on the back of the façade panel, to be connected on rails attaching to the existing building. (C) The installation of the prefabricated panel on the concrete block that bears the extra weight. Hem, France, Net-zero retrofit, under construction, Vilogia.
Source: Energiesprong International by Samyn O. (2018) https://www.flickr.com/photos/150184035@N07/albums/72157695874102660/with/43094497810/. Licensed under CC BY 2.0.

10.4.2 Design and construction principles of industrialized renovation

A number of prefabricated renovation concepts focus on the envelope optimization, limiting construction time while reducing energy demand through the use of component prefabrication (Astudillo et al., 2018; Bruno & Grecea, 2017; Bumanis & Pugovics, 2019; Bystedt et al., 2016; Callegari, Spinelli, Bianco, Serra, & Fantucci, 2015; EnergieSprong, 2014; Malacarne et al., 2016; Pihelo, Kalamees, & Kuusk, 2017; Stroomversnelling, 2014; TESEnergyFaçade, 2014). Those concepts show both similarities and differences in their approach to industrialized renovation.

The first step toward the industrialization of the construction is the decomposition of the building in different elements, which are then produced and prefabricated off-site (MORE-CONNECT, 2019). The design and construction principles of those elements can be used to classify industrialized renovation in different categories. They determine the type and size of the component, the functions to be integrated and industrialization degrees. The following sections explain the various design principles in more detail and present examples of industrialized renovation state of the art. Those examples are selected to illustrate the principles and they are by no means exhaustive. Overlaps in the characteristics and scope of the following categories can be found. The classification criterion is the building envelope construction principle, as a starting point in the design of the industrialized renovation.

Prefabricated sandwich panels

Sandwich insulation panels, also referred to as structural insulating panels, are common construction components, both in new construction and renovation. They consist of two layers of rigid panels bonded to either side of a lightweight core. The panels are typically made from oriented strand board (OSB), particleboard, plywood panels or cement-bonded particleboard or metal sheets. Those panels are preassembled and, depending on their size and functionality, they can also include prefitted windows and doors, services and finishes (Mayer, 2021). In this respect the panels' construction employs manufacturing techniques like automation and prefabrication. In renovation, they are used for improving the thermal performance of walls and roof (Fig. 10.4).

The 2ndSkin renovation concept, which is based on prefabricated sandwich façade panels to reach zero-energy dwellings (Konstantinou, Guerra-Santin, Azcarate-Aguerre, Klein, & Silvester, 2017), proposes floor-high sandwich panels, featuring new windows and integrated service installations. This sandwich panels are delivered as separate parts by the insulation product manufacturer, as in the

Figure 10.4 (A) Prefabricated roof panels used in the construction of the 12 zero-energy dwellings, in Vlaardingen, the Netherlands. (B) CompletRC RC Panels (Rc Panels, 2021) with weather finishing of brick tiles.
Source: Nunez, R.

Figure 10.5 (A) sample of the prefabricated sandwich panel. (B) Left and right panel attached to the substructure, through timber sticks. (C) Testing different cladding material.

sample in Fig. 10.5A, which are then assembled in their final configuration together with the windows in the factory. They are transported to the building site in one piece, to minimize connections between the pipes. Different cladding options are possible, applied after the panel installation (Fig. 10.5C).

Timber-frame panels

Timber-frame panels are similar to the sandwich panels since they also consist of two boards enclosing an insulated core. However, they are a distinct category as their strength comes from a framework of timber beams (Fig. 10.6) with insulation in between. Windows are also incorporated in the framework to make sure that their weight is transferred down properly. The sheathing boards, typically wooden boards, plywood boards or OSB, ensure the element's stability. Moisture and water proofing foils are also included in the panes, before the external finish.

Timber-frame panels have been increasingly used in renovation projects (Coupillie, Steeman, Van den Bossche, & Maroy, 2017; Loebus, Ott, & Winter, 2014; Ochs, Siegele, Dermentzis, & Feist, 2015; Stroomversnelling, 2019). Since the panel does not rely on the existing backing wall for stability, it is possible to replace the wall. This approach was applied by the MORE-CONNECT (2019) project, in one of the pilots, where the existing walls and balconies were removed before the new panel's connection.

Energiesprong is a whole-house renovation concept that applies the timber-frame construction principle. Over 4000 net-zero-energy houses, both new built and retrofitted, have been constructed in the Netherlands using this concept, and the first 10 performance guaranteed that net-/near-zero energy retrofits have been completed in both the United Kingdom and France (Energiesprong, 2019). The façade technical concept consists of large-scale, timber-frame insulated panels that arrive on the building site prefabricated. The openings are already integrated into the panels, based on third scanning of the existing building. The cladding material is also pre-applied to the panel, as shown in Fig. 10.7. Different options for materials are possible to match the renovation design intent.

Figure 10.6 Timber frames, stacked in the factory, before the insulation and sheathing boards are applied.

Figure 10.7 (A) The installation of the prefabricated panel on the existing façade. Hem, France, Net zero retrofit, under construction, Vilogia (B) Longueau—Rénovation thermique E = 0.
Source: (A) Energiesprong International by Samyn, O. (2018) https://www.flickr.com/photos/150184035@N07/albums/72157695874102660/with/43094497810/. (Licensed under CC BY 2.0.). (B) Energiesprong International by Singevin, F. (2018) (https://www.flickr.com/photos/150184035@N07/albums/72157701746144094j). Licensed under CC BY 2.0.

Modular façade

Modular façade (MF) refers to the exterior finish of a building made by separate, often prefabricated units (modules). The units' system, also referred to as unitized facades, is assembled in a repetitive manner on or off-site (Knaack, Klein, Bilow, & Auer, 2007). The modules should have standardized interfaces for future maintenance and upgrade (Du, Huang, & Jones, 2019). Considering the definition of a modular product as a function-oriented design that can be integrated into different systems for the same functional purpose without or with minor modifications' (Chang & Ward, 1995 in Gershenson et al., 2003), the system also provides the possibility to integrate modules with different functions. The multifunctionality is particularly important in the case of building envelope renovation when the existing building needs to be retrofitted both with passive and active measures.

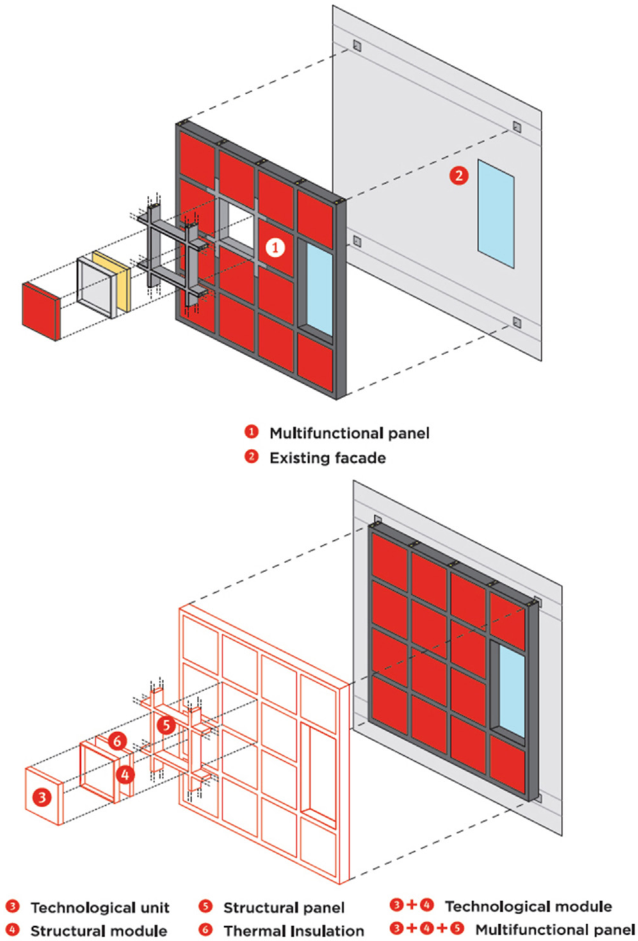


Figure 10.8 Principle of the MEEFS system, including the structural panel and the technological modules. *MEEFS*, multifunctional energy-efficient façade system (Ochoa & Capeluto, 2015).
Source: Ochoa, C. E., & Capeluto, I. G. (2015). Decision methodology for the development of an expert system applied in an adaptable energy retrofit façade system for residential buildings. *Renewable Energy*, *78*, 498–508. https://doi.org/10.1016/j.renene.2015.01.036, p. 499, Fig. 10.1.

The approach was demonstrated by the MEEFS, which stands for 'multifunctional energy-efficient façade system'. The system relies on industrialized production of the standardized panels that integrate different technological modules, allowing personalized configurations for each façade typology, orientation and local climate conditions. The façade system comprises a structural panel, made of fibre-reinforced polymer, which acts as the frame for the modules of different technologies, such as building-integrated photovoltaic systems (BIPV) and solar thermal collectors, green facades and shading (Paiho, Seppa, & Jimenez, 2015). The principle is illustrated in Fig. 10.8.

Prefabricated rainscreen facades

Ventilated façade, also referred to as rainscreen systems (greenspec, 2013) or dry-cladding systems (Thorpe, 2010), comprises the outer skin, the air cavity, the sub-structure and the insulation layer. The outer skin or panel is called the 'rainscreen', as it forms the primary rain barrier. It does not prevent the passage of air through open joints between the panelling components (Konstantinou, 2014). This type of construction is often using in renovation as it gives the possibility to upgrade the thermal resistance of the envelope, chance the external finishing and prevent moisture accumulation in the existing structure (Borodulin & Nizovtsev, 2021).

Industrialized construction of ventilated facades offers possibilities to go beyond typical construction and integrate different type of products and components off-site. One example of a renovation system based on the ventilated façade concept is the off-site prefabricated rainscreen façade, developed by the project BuildHEAT (Avesani et al., 2020). It employs a substructure that acts as the frame to host both active and passive components, connects to the existing structure and retains the external cladding. Such components include thermal insulation, PV panels, pipes and ducts for energy distribution and ventilation (Avesani, Ilardi, Terletti, Rodriguez, & Fedrizzi, 2019). The frame is preassembled off-site in floor-to-floor-height panels (Fig. 10.9).

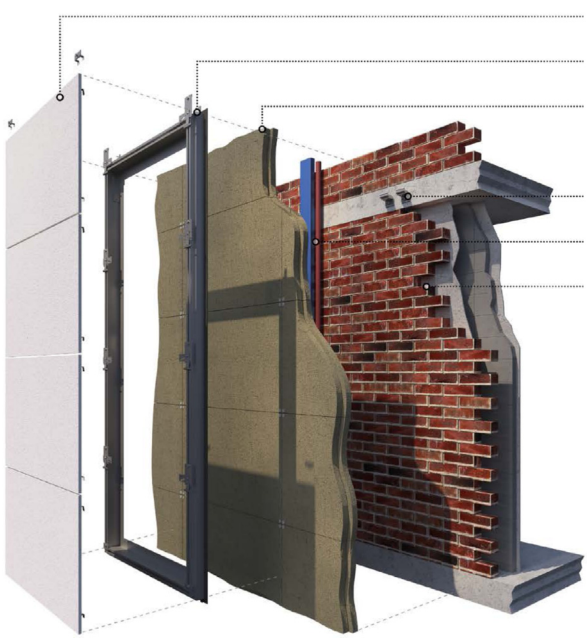


Figure 10.9 Visualization of the BuiltHEAT façade final concept and its layers (Avesani et al., 2020).
Source: Avesani, S., Andaloro, A., Ilardi, S., Orlandi, M., Terletti, S., & Fedrizzi, R. (2020). Development of an off-site prefabricated rainscreen façade system for building energy retrofitting. *Journal of Façade Design and Engineering*, *8*. https://doi.org/10.7480/jfde.2020.2.4830, p. 47, Fig. 10.2, licenced under CC by 4.0.

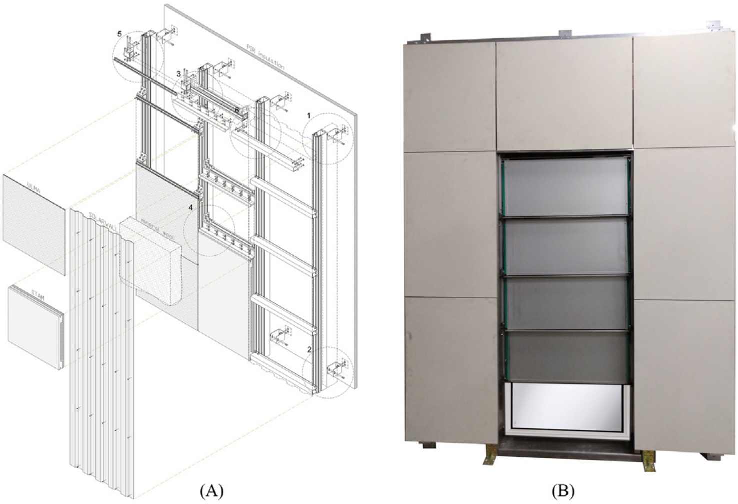


Figure 10.10 (A) Different systems to be integrated into the substructure of the BRESAER renovation system, (B) mock-up of the system (Aguirre et al., 2018).
Source: Aguirre, I., Azpiazu, A., Lacave, I., Álvarez, I., & Garay, R. (2018). BRESAER. In *Breakthrough solutions for adaptable envelopes in building refurbishment VIII international congress on architectural envelopes, San Sebastian-Donostia, Spain*; Figs 10.2 and 10.3, © EURECAT and LKS KREAN.

Capeluto (2019) describes how the BRESAER system, which stands for breakthrough solutions for adaptable envelopes in building refurbishment, can adjust the components to allow for adaptability to different climates and requirements. It consists of a lightweight structural mesh that integrates active and passive prefabricated solutions. Following the idea of rainscreen facades, an aluminium frame supports components such as lightweight industrialized ventilated façade module, insulation panels made of ultrahigh-performance fibre-reinforced concrete and dynamic windows with sun protection (Fig. 10.10A and B). All the systems are exchangeable and removable, facilitating the maintenance and the adaptation of the façade system (Aguirre, Azpiazu, Lacave, Álvarez, & Garay, 2018).

Preassembled configurations

As discussed in Section 10.2, renovation and particularly deep renovation needs to comprise a variety of technologies, from thermal insulation to renewable energy and upgrade of the building services components. Industrialization supports the effective integration of components in the building envelope, limiting the installation time, space requirements and occupants' disturbance. The different components to be retrofitted, such as internal and external heat pumps units and the water buffer tank, can be preassembled and placed in prefabricated constructions, which are then transferred to the construction site and installed on top or on the side of the existing building envelope.

Figure 10.11 Preassembled building services unit placement on the roof. Factory Zero, the Netherlands, energy modules.
Source: Energiesprong International, 2019, https://www.flickr.com/photos/150184035@N07/albums/72157690034665123. Licensed under CC BY 2.0.

An interesting concept that follows this principle was developed by the company Factory Zero. The concept's main innovation is the integration of the building services in the Climate Energy Module (Factory Zero, 2020), which can be installed during the roof renovation, as seen in Fig. 10.11. It combines an insulated roof panel with a plastic hood that hosts the heat pump outdoor unit and the foils and binders to connect to the rest of the roof construction.

Overview of design concepts

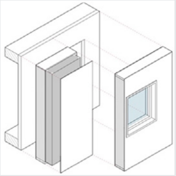
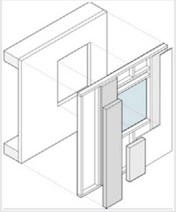
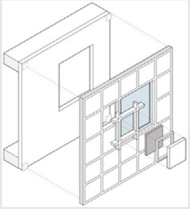
The previous principles refer to design and construction concepts that apply degrees of industrialization to upgrade the building envelope as a whole or parts of it. They can be combined with each other or with on-site renovation technologies. Table 10.2 presents an overview of the design concepts, providing a brief decription of the principle, indicative reference projects and degree of industrialisation.

Two overarching categories can be identified; components consisting of an insulation core and sheathing layers and components that consist of different modules. Modularity is a common characteristic of all concepts, to different levels and sizes. The special mention of MF as a distinct category refers to the different function of each module. The prefabricated rainscreen façade can also be considered a subset of the MF. However, it differentiated from the type of substructure that is based on the construction principle of the ventilated façade. Finally, it is worth highlighting that the preassembled components' concept is distinct from the previously discussed building envelope concepts, and it can be supplementary to other industrialized or on-site renovation approaches (Table 10.2).

10.5 Outlook for the future

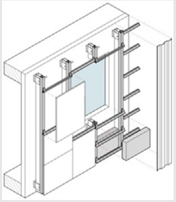
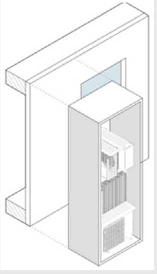
Next to the improvement in energy efficiency, indoor climate and environmental impact that renovation achieves, industrialization has additional benefits, which can also be considered drivers for further development (D'Oca et al., 2018; Hong et al.,

Table 10.2 Overview of the applicable design concepts, linked to reference state-of-the-art projects, and most important degree(s) of industrialization.

Design principle			**Reference project**	**Degree of industrialization**
Prefabricated sandwich panels		• Two layers of sheathing boards bonded to either side of a rigid insulation core • Different options for the boards and insulation materials • Possible prefitted windows and finishing	• 2ndSkin: zero-energy apartment renovation via an integrated façade approach (Konstantinou et al., 2017) • Rc Panels (Decorte et al., 2020; Rc Panels, 2021)	Prefabrication Mechanization
Timber-frame panels		• Load-bearing timber frame, sheathing boards, insulation in between studs, moisture and waterproofing foils • Windows incorporated in the framework	• MORE-CONNECT (MORE-CONNECT, 2019) • Transformation Zero (Energiesprong, 2019)	Prefabrication Mechanization
Modular façade		• Exterior finish of building made by separate, prefabricated units (modules) • Modules with different functions • Modules connected directly to existing structure or incorporated in a frame • Standardized interfaces	• MEEFS, (Paiho et al., 2015)	Prefabrication Reproduction

(*Continued*)

Table 10.2 (Continued)

Design principle			Reference project	Degree of industrialization
Prefabricated rainscreen façade		• Outer skin (rainscreen), the air cavity, the substructure and the insulation layer • Outer skin consists of prefabricated, passive and active elements • Based on the principle of ventilated façade, which can be assembled off-site	• BuildHEAT (Avesani et al., 2020) • BRESAER (Aguirre et al., 2018), (Capeluto, 2019)	Prefabrication Reproduction
Preassembled configuration		• Components preassembled and placed in prefabricated constructions • Installed on top or on the side of existing building envelope • Combined with other industrialized or on-site renovation measures	Factory-Zero (Factory Zero, 2020)	Prefabrication Mechanization

MEEFS, Multifunctional energy efficient façade system.

2016; IEA Annex 50, 2012; Jaillon & Poon, 2014; MORE-CONNECT, 2019). The main benefits of industrialized renovation are related to the potential for the following aspects:

- effective strategy for improving the productivity of the construction industry (mass and scaling) to make upscaling possible;
- cost reduction through the economy of scales;
- reduced on-site construction time and disturbance for occupants;
- quality assurance of manufacturing by prefabrication and integration;
- design and engineering efficiency (scanning, simulation and optimizing) is an integral part of the industrial process; and
- environmental and economic benefits related to the reduction of construction waste and material use.

To achieve those benefits of industrialization, the renovation market requires process, marketing and organizational innovation (BPIE, 2016). The following sections elaborate on the aspects that can support the further developments and implementation of industrialized renovation.

10.5.1 Adaptability and circularity

The larger amount of production is at the core of what makes industrialization possible and meaningful (Richard, 2005), which is also in line with the need to upscale renovation to reach the goals for decarbonization of the built environment.

Of course, the building stock is not homogeneous. To be able to apply industrialized renovation in a large number of buildings, there is a need for customized solutions. Using prefabricated envelope elements might sound like a disparity to reach adaptability since mass production components have more or less fixed characteristics (Capeluto, 2019).

The key characteristic of the industrialized components should then be adaptability. Adaptability in manufacturing can be achieved if the whole system is based on the combination of various components and allows for small but significant changes decided during the design stage, which can be implemented during system manufacturing according to demand (Capeluto, 2019). The solution needs to combine a general baseline concept, which can be manufactured in an industrialized way while being able to vary in a rationalized/systematic way.

Moreover, upscaling the renovation also means increasing the material and the energy use for their manufacturing and construction. The construction sector accounts for 38% of the waste generated in the EU, more than any other sector of the economy (European Construction Sector Observatory, 2018). Within the context of decarbonization, renovation approaches need to adopt life cycle thinking that aims not only to be more energy-efficient but also less carbon-intensive over their full life cycle. Applying circularity principles to building renovation will reduce material-related greenhouse gas emissions for buildings (European Commission, 2020).

Modularity and adaptability are key principles for the design of a circular built environment. Off-site construction and modularity reduce the amount of waste produced on-site and enable reuse and repurposing (Arup, 2016). Industrialized construction of the retrofitted components offers advantages to that respect. Modularity and disassembly that are inherent properties in industrialized construction support the application of circular design principles, such as reuse, replace and remanufacture of components and materials (Durmisevic, 2010).

10.5.2 Process optimization

As already discussed, the complexity of holistic application of prefabricated modules in renovation, integrating both the building envelope and building services, is increased. However, it is also essential to achieve high-performance results in energy upgrade. Additional issues that hinder the application of large prefabricated components are logistics limitations, for example, the lack of on-site storage (Jaillon & Poon, 2014). Optimizing and standardizing the process, from design and manufacturing to construction and supply-chain collaboration, can help overcome those problems. Current digital technologies, such as image-based 3D reconstruction (Ying, Lu, Zhou, & Lee, 2018) and BIM (Aldanondo et al., 2014), support this process optimization.

10.5.3 Renovation market

The adoption of industrialized renovation concepts by the building industry requires higher initial costs (Jaillon & Poon, 2014), and investment in equipment for mechanized construction, to reach sufficient capacity (Kamaruddin, Mohammad, & Mahbub, 2016). The lack of those investments hinders the uptake of industrialized renovation.

To overcome such barriers the demand is key to motivating investment in industrialized manufacturing and process optimization needed for the paradigm shift from traditional renovation techniques. As for every product, the market share that is the target should be considered and analysed. Looking at country level, BPIE (2016) has identified the characteristics that result in higher potential for industrialized renovation market integration. Those characteristics are the mature prefab construction market for new constructions, existing building stock in need for renovation, the availability of suitable building typologies for an aggregated prefab construction approach, such as (social) housing, apartment blocks and offices.

10.5.4 Renovation as a product

To increase the market uptake of industrialized renovation, the building industry needs to innovate and look at the renovation not only as the technical challenge but also as a product. Platform- and product-oriented building companies have prerequisites in their company structures and setups that include opportunities to further develop their business models. By following the same paths as other product-oriented industries, industrialized building companies could extend their physical offerings by combining them with services throughout the products' life cycles (Lessing & Brege, 2018), providing the renovation as part of a holistic approach, and combining the technical upgrade with models, such as energy contracting, addresses financial barriers and fragmentation of the supply chain.

Examples of such approach can already be found. In the renovation approach of the Energiesprong (2019), previously discussed in Section 10.4.2, the energy retrofit with industrialized components is combined with a long-term performance guarantee on both the indoor climate and the energy performance. The principle is that the money the residents normally spend on energy bills and maintenance over time is used to finance the retrofit. In this way the total cost of living for the residents remains the same, while their home's quality improves. Similarly, the 2ndSkin project (BIKBouw, 2017) offered zero-energy use of the renovated appartments combined with energy performance contracts. This approach resulted in a viable business case for the housing association, who financed the renovation without increasing the rent after the renovation.

10.6 Conclusion

This chapter discussed industrialized renovation of the building envelope as a way to increase the rate and depth of renovation in the building stock, which are necessary to eliminate carbon emissions from the building sector in the following decades. Industrialization of the retrofits is an effective strategy for improving the productivity of the construction industry, to achieve high performance in existing buildings while minimizing on-site construction time.

Industrialization in the construction, and renovation in particular, has several degrees, from automation and mechanization to robotization and prefabrication. Those degrees are already applied and combined in renovation practice. However, industrialized renovation should go beyond standard practices and aiming to maximize reproduction and off-site construction, through an effective combination of all degrees of industrialization, to target deep renovation at large numbers.

With regards to industrialized renovation of the building envelope, there are different design and construction concepts that can be used. They all aim at high energy performance of the renovated building and incorporation of different technologies that are needed, while making the use of the benefits industrialization for minimizing on-site time, high productivity and quality assurance. Deciding on a concept determines not only the renovation strategy but also the manufacturing and installation techniques and facilities. Therefore it is an important starting point toward industrializing the renovation.

Despite the benefits of industrialized renovation and the several successful state-of-the-art examples, the market uptake is still slow, leaving the potential underexploited. Next to the general barriers to energy renovation, some more specific barriers to industrialized renovation are related to the high initial investment to set-up the production, as well as addressing the adaptability of the concept that is necessary in the heterogenous existing building stock. To overcome those the building industry should focus into more integrated solutions combined with business models, make use of current digital technologies to aim at mass-customization, and collaborate with the demand site and policymakers to target large numbers of buildings to reduce the cost through reproduction.

To achieve that, industrialization of the renovation needs to be made part of the supply chain operation and be prioritized in the strategic decision-making. When successful, thought, industrialized renovation will help overcome some of the challenges of the renovation market such as high costs, lack of capacity, lack of information and fragmentation in the supply chain. In this way the potential of the building stock for decarbonization and sustainability can be realized.

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