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TRANSFORMATION AND ACCELERATION OF THE CONSTRUCTION SUPPLY CHAIN THROUGH SMART FACTORIES

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Abstract. The European building stock is in high need of refurbishment due to its contribution to excessive global energy consumption. In the North-Sea Region (NSR) alone there are 22 million houses built between 1950 and 1985 with an annual CO_2 emission of 79 Mton. Current deep retrofits are carried out on a limited-scale production, which may result in climate targets not being met in time. To tackle the need for rapid renovations, prefabricated insulation elements with integrated intelligent technologies, manufactured in novel smart factories using mass customization, could offer a solution. This approach is also followed by the Interreg project INDU-ZERO. The project examines a far-reaching automated production and develops a blueprint for a smart construction factory in the NSR that can produce 15 000 renovation packages per year. This paper aims to quantify the acceleration potential of the supply chain by improving its production, logistics, and on-site mounting processes for Dutch single-family terraced houses. First, the design of the renovation packages and smart construction factories are introduced. Then, the procedure is elaborated on how the supply chain can be abbreviated. The results show that the renovation cycle time can be completed within two weeks through coordinated efforts between production, logistics, and mounting.

Keywords: Smart factory, renovation cycle time, supply chain.

1. Introduction

Industry 4.0 still inspires the manufacturing industries and leads to the introduction of new technologies every day. Driven by the fourth industrial revolution, companies are investing in the development of smart factories with the aim of integrating digitalization into fabrication structures [1]. By creating an autonomous production and logistics environment in which machines, systems and vehicles communicate independently with each other, companies hope to remove humans from manufacturing processes in order to operate more efficiently [2].

Undoubtedly, the building industry seems trivial with its rather stereotypical processes and analogue techniques compared to the pioneering power of the mechanical engineering industry [3]. In the near future, a major restructuring has to take place to tackle the high need for renovation of the building stock as here caused CO_2 emissions contribute to around 36 % of the European CO_2 emissions [4, 5]. To achieve the EU's climate targets, about three million buildings per year should be renovated in Europe in the period 2022–2030. However, the renovation speed is too low to deal with these numbers. Today, there are only a few production facilities that can offer renovation solutions for a maximum of 500 dwellings per year. In this case, each dwelling is still supplied with specially tailored proposals and the work is mostly done on-site. As a result, the costs of renovations to energy-neutral homes, which often exceed €110 000 per unit, is too high to convince homeowners of an energetic renovation [6].

Therefore, six NSR countries collaborate in the Interreg project INDU-ZERO "Industrialization of house renovations toward energy-neutral" to upscale the renovation process with a focus on the renovation of the NSR housing stock and to design a smart factory blueprint to produce 15 000 fully integrated prefabricated renovation packages per year per factory. These packages consist of facade and roof panels, which are complemented by photovoltaic systems as well as heat pumps and ventilation systems. The aim of the design is to achieve energy-neutral dwellings in one-step. The project definition of energy-neutral implies that the energy demand is fully compensated by renewables on an annual basis. The energy demand for household appliances, lighting, material extraction, production and distribution is not included [7].

The facade and roof panels are developed considering several design boundaries such as production

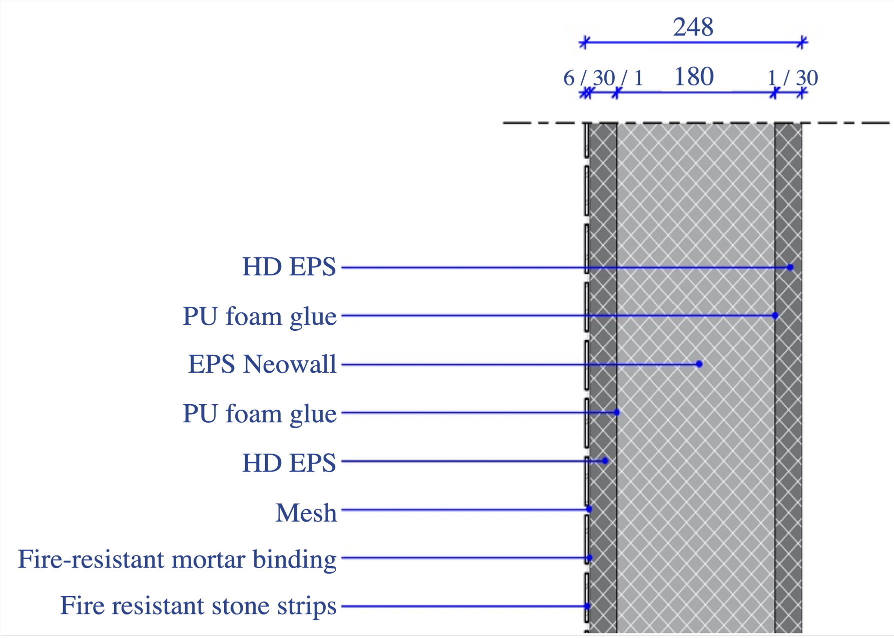

Figure 1. Assembly of the wall component design: sandwich panel.

speed, environmental impact on CO_2 reduction and total cost of ownership. They are designed for semi-detached houses, terraced houses and apartment buildings built between 1950 and 1985, representing 30 % of the housing stock in the NSR. To meet the market demand, all steps are planned in cooperation with social housing corporations and house owners. The structure of the developed renovation packages is independent of a specific project or building. The aim of this mass-customized approach is to eliminate construction as well as on-site complexities and constructability issues, as the panels always follow the same production and mounting processes. Moreover, the packages have to be pre-assembled as much as possible before being transported to the construction site, to cut down labour time, total costs and nuisance on-site [7]. Figure 1 shows the build-up of the INDU-ZERO facade sandwich panel, which largely consists of HD and LD EPS, held together by polyurethane foam glue and complemented by mesh, fire resistant mortar bonding and the outer facade layer. The difference between a facade and a roof panel is that the roof panel is equipped with PV systems instead of fire-resistant stone strips, which are also already installed during the automated production process.

In five previous papers, published as part of the project, the moisture assessment, environmental impacts and global warming potential of the shown panel and prefabricated renovation systems, energy demands of the supply chain, as well as the data chain of the smart factory were analysed [6–10]. In contrast, this paper focuses on the acceleration potential of the construction supply chain through smart factories by improving its production, logistics and on-site mounting processes exemplarily illustrating the renovation cycle of a single-family terraced house in the Netherlands and comparing it with the current duration.

In course of this paper, times of current and future supply chain processes are explained collectively and at the end compared in a resuming table. The outline is as follows. The applied methodology is introduced in Section 2. Section 3 presents the current supply chain processes and its future transformation through the implementation of smart factories. The renovation concept as well as acceleration potential is shown in Section 4. Finally, Section 5 discusses the results, summarizes the recommendations for future research and concludes the paper.

2. Methodology

The methodical procedure is based on the Method of Structured, Focused Comparison developed by George and Bennett, as their approach allows case studies to be compared with previous published work [11]. As presented in their research, the case study developments must explore the same phenomenon, pursue the same research goal, adopt equivalent research strategies and select the same focus [11]. To follow the approach in a proper manner, this paper is being carried out by the three steps illustrated in Figure 2.

First, a comprehensive literature review of the current processes in the construction supply chain is conducted to show how these are changing through the implementation of smart factories. The first step and its results are complemented using the INDU-ZERO case study to calculate and illustrate the acceleration potential of production, logistics and assembly. In this course, individual methods are used to measure the future times in the three areas of observation. These are explained in each subsection in Section 4. Subsequently, the specifically identified times of the current and future supply chain are compared and paired.

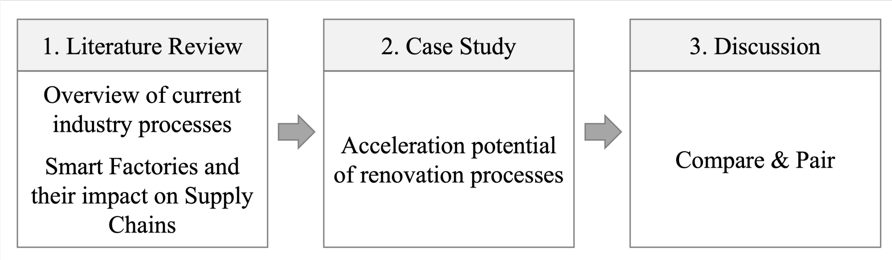

Figure 2. Research process.

3. Transformation of the construction supply chain through smart factories

The following chapter examines the impact of the implementation of smart factories on the supply chain compared to current industry processes and presents the changes that will result.

3.1. Overview of the current industry processes

Generally, architecture and construction have a low level of industrialization and automation compared to other industries, as only buildings with low technical complexity, such as parking garages, hall buildings or supermarkets, have been recommended for prefabrication. In addition, the following reasons for the low level of automation and digitization in the retrofit market can be identified [12]:

- Manufacturers and suppliers of products are mostly small companies. There is a lack of original equipment manufacturers and production structures on an industrial scale that can make the necessary investments to build up autonomous production facilities.
- Due to the predominantly artisanal production as well as rigid organizational structure, trade unions exist that defend the market and thus prevent an overarching approach.
- Due to the products and materials used in the popular solid construction, it is difficult to automate the production processes, as the raw materials require analogous approaches.
- Workload in the industry is too high. The construction industry is struggling with a serious labour shortage due to demographic change and simultaneous boom in the real estate market.

It is not uncommon to hear that the current supply chain in the construction industry is different from other industries, since there are no factories at its centre. In most instances, raw materials (e.g. clay) are either transported to producers for building materials (e.g. bricks) and after further processing to the construction site, or directly to it, where they are used for building or renovating the house or apartment. Most projects are realized with a design-to-order or engineering-to-order approach. Each building is supplied by means of tailor-made offers from scratch and most of the work is carried out manually on-site.

Considering current standards and norms, such as the Dutch Building Decree or German Building Code, and application of conventional renovation technologies, the energy renovation of a building to a zero-energy house here takes up to four weeks. In Scandinavian countries, this can take even longer, as timber construction is not as easy to refurbish as solid construction, since the wooden facade incl. vinyl tarpaulin must be dismantled, and the humid climate also negatively affects construction site processes [8]. The most time-consuming parts are spent on measuring and design, which takes around three days, and the energy retrofit itself, which takes around seven days for a single terraced house. On the one hand, this is due to the fact that the share of prefabrication has been very small so far. On the other hand, production, transportation and construction processes are only partially coordinated, because cooperating companies do not have necessary capacities. In this way, these procedures are completed one after the other and not simultaneously. This shows the result of the qualitative surveys conducted among three Dutch housing corporations.

3.2. Smart factories and their impact on construction supply chains

The expectations for Industry 4.0 are augmented transparency, traceability and process optimizations to reduce repair as well as maintenance costs while increasing machine availability and efficiency [3]. In the future, it will be possible to produce entire house units in a decentralized manner in smart construction factories that aim for a standardized, cost-effective and faster production of residential properties compared to conventional construction on-site processes [13, 14]. Standardisation is highly developed to have a more cost-effective and faster production due to a configure-to-order approach. Products no longer have to be designed from scratch, only slight adjustments need to be configured.

By manufacturing according to an industrial scale, housing shortage can be counteracted. Furthermore, these factories can target the market for old buildings and renovation projects as the production of customized renovation packages is also possible [15].

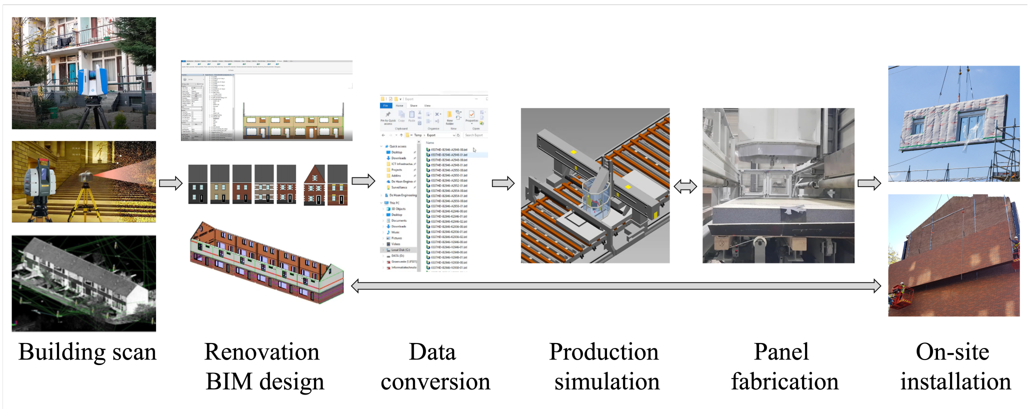

Figure 3. Future INDU-ZERO construction supply chain process overview.

Figure 3 shows the future INDU-ZERO construction supply chain process overview.

The smart factory adds another value adding process step to the supply chain, as materials are now no longer transported directly to building sites. In particular, these factories rely on created point cloud and BIM models of houses being renovated. Based on the derived number of windows and doors and the square meterage of the facade, they can manufacture panels to the millimetre. Furthermore, the factory, as the centre of the supply chain, continues to have all necessary data of procurement and distribution. Based on digital connections in Industry 4.0, the factory knows at what time which materials have to arrive and when production has to take place in order to transport the panels to the construction sites on time [16]. It can coordinate production, logistics as well as mounting process simultaneously without having to consider individual priorities from other companies. In this context, production planning has to consider how the processes of incoming goods, warehousing, production and outgoing goods can be controlled by cyber-physical systems [17].

For independent architects and designers, in particular, this means they can be bypassed in some tasks in the new, transformed value chain. Where previously customers consulted architects to design their home retrofit, they now contact the factory or their agents directly. Once the house has been measured and digitized via 3D scan, customers configure the new design themselves. Afterward, engineers and architects, who work for the factory, only need to check that structural requirements have been met and that the new design adapts to the neighbourhood.

The results of INDU-ZERO show that the realization of smart factories in the construction industry is possible. Regarding a potential market acceptance, the project identified that not only housing associations, but also governments, industry and investors are increasingly interested in the implementation, since, in addition to the reduction of renovation costs, numerous jobs are created in the factory and on the construction sites [18].

4. Acceleration potential of renovation processes

The time advantages resulting from smart factories are explained in detail in the following chapter.

4.1. Production

The aim of smart construction factories is the standardized, cost-effective and faster production of residential properties compared to conventional construction processes, in which buildings are constructed manually on-site [13]. The production of the facade element in Figure 1 requires a number of manufacturing processes shown in Figure 4:

- A wire cutter slices the LD EPS panels to the right length;
- HD and LD EPS panels are glued together and pressed until bonded firmly;
- The CNC milling machine accurately shapes the panels outer dimensions and cuts out the apertures for windows and doors;
- HD EPS fixation blocks are then attached to the sandwich panel;
- The panel is then reinforced with a fiberglass mesh;
- The external finishing is attached to the sandwich panels, e.g. plaster or wood strips;
- Windows and doors are mounted into the panels;
- Electrical cabling is integrated in the panels;
- The quality of the panel is controlled using latest vision-based technologies;
- Panels are sorted and packed on racks by bundles;
- The racks with the panels are then stored before the shipment.

All factory processes were adjusted in detail with the software Tecnomatix Plant Simulation and thus provide reliable process times that can be used as a reference for a later reality. The above shown production process takes five hours to complete. Moreover, before the materials are brought to the production lines,

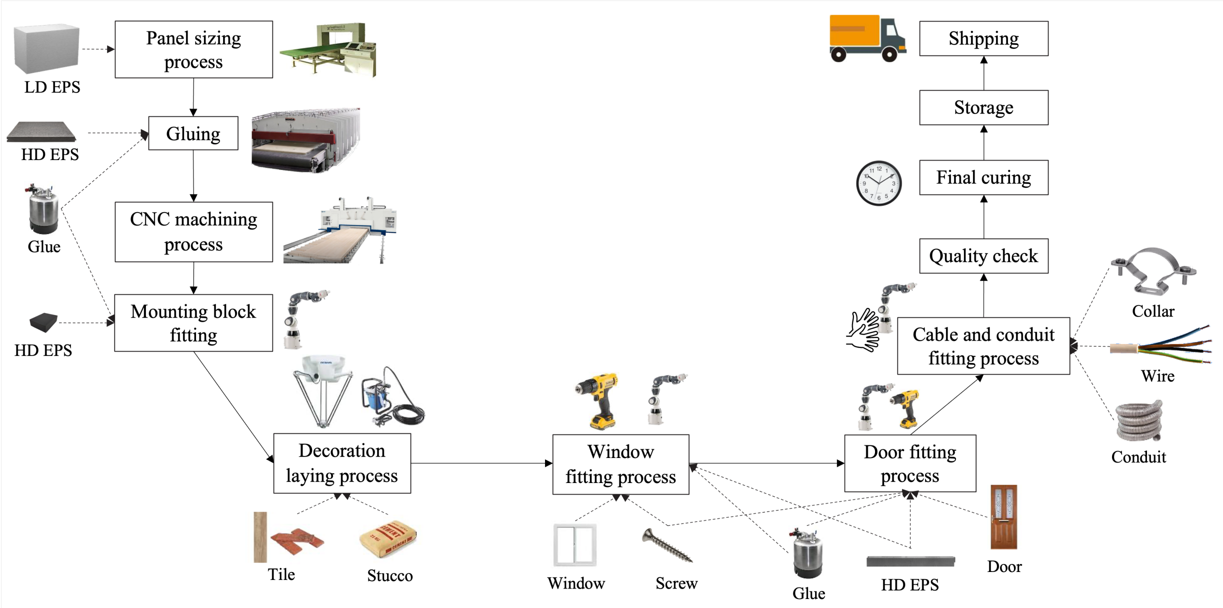

FIGURE 4. Smart Construction Factory production process and used machinery.

trucks have to be unloaded, materials have to be separated and assigned to the panels, and a quality check in the incoming goods department has to be carried out, which takes two hours. After production, the glue has to cure for another 24 hours before the panels can be transported to the construction sites.

4.2. LOGISTICS

Just as production can be simulated in the future by digital twins or buildings by BIM, logistics can also be planned, replicated and controlled in real time by digital supply chains. In conventional logistics, the parties involved in a value chain tend to appear like rigid members acting separately along a linear supply chain. INDU-ZERO aims to break up this chain and replace it with a flexible network. The focus is on the development of open, digital ecosystems that support the ability to communicate on the market. Through them, incompatible interfaces resulting from communication between people, machines, and companies can be closed. Thus, the normative planning area as well as the operational machine area are now decoupled from the physical material flow and decisions are made decentrally on basis of the available real-time information.

INDU-ZERO serves not only as an example for the autonomous production of 15 000 renovation packages per factory, but also for the design of an intelligent supply chain. The transport of the building materials from suppliers to the smart factory and subsequent to the construction sites play a decisive role, as the logistics processes are also time consuming and can considerably contribute to the overall CO_2 emissions. In contrast to the current production of individual materials and their use in renovation, INDU-ZERO requires additional transport distances in the supply chain, since raw materials first have to be brought to the smart factory, where they are integrated into the renovation packages. Consequently, it is aimed to also offset the here caused extra time as well as CO_2 emissions.

This can be achieved by digital supply chains and an appropriate location planning. By using digital supply chains, procurement, production and distribution logistics can be planned automatically on the basis of predefined criteria. For example, any inventories held by different suppliers are linked online. If one supplier is unable to deliver the required quantity, capacities are compared and other suppliers are automatically commissioned with the supply. In distribution, building sites that are in close proximity to each other can be combined, so that empty runs or additional transports can be avoided.

Since the supplier locations have already been identified, the future factory can be located in their vicinity to avoid long transport distances. On average, the current transport distance from the suppliers to the manufacturers of the products is 130 km per route in the European construction industry. This is followed by another 100 km to the construction sites. The regular transportation time is four days and the procurement of materials takes two days [19]. Due to the sophisticated location planning, the average transport distance can be reduced to around 60 km per route in INDU-ZERO. This results in time savings of over in 60 minutes per way [7]. As roughly four trucks, transporting the raw materials for the production, per dwelling are needed, the location planning saves over eight hours of transportation time. In the end, the additional transport in the supply chain is offset by the mentioned measures, because the total time of the distribution process can thus be reduced to three days.

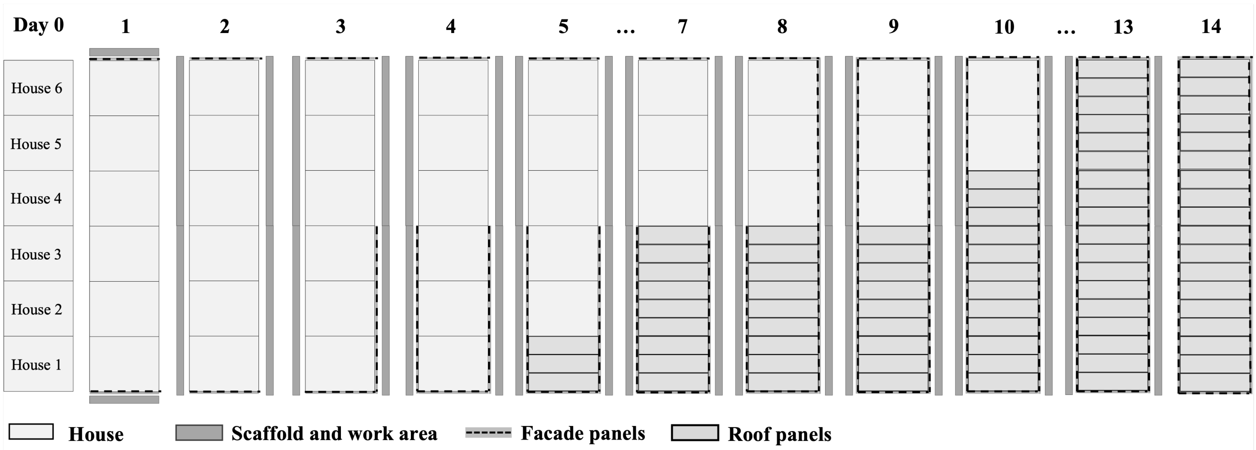

Figure 5. Process and planning of a six-dwellings terraced house.

Process	Current time consumption	Future time consumption
Measurement and design	3.5+ days	1.5 days
Procurement	2 days	2 days
Production	0 days	1.25 day
Distribution	4 days	3 days
On-site mounting	7+ days	3 days
Total	**16.5 days**	**10.75 days**

Table 1. Current and future time consumption for renovating a terraced single-family dwelling.

4.3. On-site mounting

On-site mounting covers, depending on the project, about half of the total cost and most of the time of a renovation. The purpose is, equally to the main target, to reduce the current cost and time by around 50 %. Furthermore, the duration of the nuisance for the residents should also be avoided as far as possible. Innovative machinery (i.e. suction mechanisms for sand and rooftiles, "chimney grabbers" or drones for drilling holes) can be a solution to replace as much human labour as possible, dismantle the current dwelling components as well as mount the new renovation packages. Therefore, simulation tools with gamification are used to train machine operators.

Figure 5 represents the on-site mounting process of a six-dwellings terraced house according to INDU-ZERO. The times are based on a real-life energetic renovation of a Dutch single-family terraced house following the INDU-ZERO concept as well as the experience of Dutch housing corporations and their general building contractors interviewed as part of the qualitative survey, which have previously refurbished houses with prefabricated facade elements [20]. The process shows that a block of dwellings can be renovated in 14 days by five workers. In the first day, typical preparations are made and end facade elements are mounted, while precaution measurements are executed for mounting the elements during the second day. Day three and four cover the mounting of the facade elements. In turn, the roof panels are mounted from day five till seven. After seven days, the first three dwellings are finished, but remain part of the building site because there are still safety issues for the finished dwellings since they may experience nuisance of heavy machinery like cranes. From day eight till 13, the same cycle repeats for the next three dwellings. Day 14 is dedicated to finish the renovation. In the end, the renovation time amounts three days per dwelling on average.

4.4. Time saving potential of the renovation process

Based on the previous results, Table 1 can be generated, which summarizes the current and potential future timeline for renovating a Dutch terraced single-family dwelling. The insights of the current time consumption were gathered from the mentioned surveys and overall renovation experience. The future time consumption results from INDU-ZERO's research in Section 4.

The implementation of smart factories can shorten the duration of the supply chain processes by at least six days to a total of 10.75 working days. In the measurement and design phase, two days can certainly be saved, since the renovation packages no longer have to be redesigned from the beginning, but only adapted. Typically, the design can take several weeks, depending on the individual wishes of the residents and housing corporations. Smart factories make use of predefined components and designs, similar to an automobile configurator, and reduce the required time to less than two days. Intelligent location planning can further shorten the distances from suppliers to the factory and from there on to the construction site by one day. However, the production process adds another day here. The procurement time of two days is hardly affected and can only be made more flexible, as the process times continue to be influenced by the suppliers. Another reason for the reduction in duration is the digital supply chain, as it creates a digital image of all real processes. Consequently, these can be planned in a timed manner several weeks in advance in order to simulate any processes and possible incidents. One of the biggest time differences can lastly be seen in the installation processes on-site. Here, prefabrication, smart machinery and well-designed work processes can save around four days.

5. Discussion and conclusions

This paper showed how the construction supply chain processes can be transformed and accelerated through the integration of smart factories following the Method of Structured, Focused Comparison by George and Bennett. In total, the entire process can be completed within two weeks through coordinated efforts between production, logistics, and mounting. Within ten days after being measured, buildings can be renovated in a climate-neutral way with less waste production on site.

The study is limited to single-family terraced house dwellings in the Netherlands. However, it can be assumed that the renovation times for other types do not differ greatly from the result, as production and logistics processes remain identical. Nevertheless, there may be positive or negative deviations in measurement and assembly, depending on the structure and environment of the building, such as the dismantling of a dilapidated wooden facade including vinyl sheeting in the Nordic regions.

As there has been some previous investigations [6–10], the JIT supply of prefabricated panels to construction sites or the in-depth investigation of different installation processes can be proposed for future research. There remains also the fundamental question of how home and energy neutrality offset the cost of refurbishment, since housing associations bear the costs but residents save on energy costs. In the end, the construction companies and housing corporations are being forced to push themselves ahead with digitization in order to meet the specified climate guidelines on-time whether with or without smart factories.

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