Enhanced Productivity for the Future of Retrofitting

M Deffner¹, M Dorresteijn¹, B van Elven¹, H Koene¹, R Laterveer¹, M van Os¹, M Smilde¹ and T Topper¹

¹ Utrecht University of Applied Sciences, Padualaan 99, 3584 CH Utrecht, the Netherlands
E-mail: ar.retrofitting@gmail.com

Abstract. With the growing effects of climate change, it has become of great importance to reduce emissions from the building stock. Climate friendly retrofitting of dwellings has emerged as an important role since then. Based on a case study in the Netherlands and scientific research on the associated processes, it is concluded that the state of the current retrofitting process is not productive enough to meet European climate goals. To satisfy the increasing need for retrofitting, the Axiomatic Design Method is used to track down the key findings to improve the output of the retrofitting process from a holistic perspective. The aim of the research is to contribute to increase the current output of 50,000 residential retrofits per year by 300% for the Dutch construction industry. The results give opportunities for improvements that should be made within the process, product, and regulations in the industry. The elimination of manual labour in roof renovation is the finding that has the greatest impact on process productivity. In addition, the changeover of the process has an impact, whereby scaffolding, fall protection and weather no longer have an influence or are no longer required. It can be stated that efficiency could be significantly increased with low manual labour roof retrofitting.

Keywords. productivity in construction, roof retrofitting, panel insulation, process improvement.

1. Introduction

The world is facing the challenge of reducing greenhouse gasses to prevent further global warming. Thereby, the consequences of too much greenhouse gasses in the atmosphere have a devastating effect on life on Earth. For example, the probability of floods and droughts will increase [1].

Within total emission, the building sector represents 37% of the total energy related CO₂ emissions worldwide in 2020. In addition, residential and non residential buildings cause 27% of the total CO₂ emissions worldwide [2].

By taking a closer look at the energy consumption of residential buildings in the European Union (EU), it becomes clear that 63.6% of energy was used for heating in 2019 [3]. From 1970 onward, most of the European housing stock is largely energy inefficient, as there were no clear regulations for thermal insulation requirements at that time [4].

Governments around the world have already taken strong measures to increase the number of
retrofitted dwellings [5]. The annual renovation rate must grow, as the building stock has the greatest potential for energy savings in the EU. This provides the best opportunity for achieving the EU’s objective of reducing 80-95% of greenhouse gas emissions by 2050 compared to 1990 [6]. In 2020, the renovations that reduce the energy use in buildings by 60% were carried out in only 0.2% of the total European building stock. At this rate, the reduction of CO2 emission from the building stock towards a net zero industry would take too long, which supports the EU's statement: "It is time to act" [4].

With the so called Renovation Wave Europe, the goal of renovating 35 million inefficient European houses by 2030 is set [4]. Thus, the necessity for a scalable, time and cost efficient insulation process is given. As part of the EU and as a pioneer of decarbonisation in the construction sector, the Netherlands is involved in projects such as ARV (of the EU green deal) and the North Sea Region’s program INDU-ZERO. It is also funding other projects related to reducing the gap of 150.000 retrofits per year [7], for example, the Future Factory and the Technology Innovation Center. This makes the country and its construction industry a suitable context for this research.

2. Problem statement
The construction industry is characterised by construction onsite with outdoor conditions. During the case study, it was discovered that professional workers employed in these outdoor settings must consider their own safety, as well as the safety of the occupants and others who use the public space surrounding the retrofitting site. Besides maintaining vigilance, they must also deliver adequate installation quality, which is influenced by the previously mentioned conditions. In addition, the construction labour cost typically is 30-50% of the total project cost, it is desirable to work as fast as possible. Construction using manual labour is characterised by a high number of steps that do not directly add value to the result [8]. This in turn leads to low productivity [9].

Construction companies are among the least performing industries due to their lack of effectiveness and productivity [10]. The foremost reason for this is the human factor, but weather conditions also play a role [11]. This, together with low standardisation, manipulation of large objects, and low tolerances, make the traditional construction industry an important and challenging topic for research [12].

2.1 Main research question
This research aims to provide the improvements necessary to eliminate manual labour from roof retrofitting to enhance productivity. The focus is on roofs because of the additional complexity compared to facades. Robotising is indispensable for meeting the challenges of scaling retrofitting efforts in Europe. It also creates a safer work environment, ensures good product quality, and increases the overall cost effectiveness of the solution.

To summarise the problem statement and to contribute to the increase of productivity in the construction industry, the research question is set in the given context as follows:

"How can the roof retrofitting rate of dwellings be increased by improving the productivity of the (Dutch) construction industry?"

3. Applied research method
To answer the research question, Quantitative Design Research is used. This method finds areas for improvement in the current process to enhance productivity. Furthermore, this type of research is a commonly used method and starts with creating a clear picture of the situation by analysing the current process and data [13]. The project is then divided into the areas of process, technical and regulations in order to be able to proceed in a more targeted manner.

First, the process elaborates on the actions necessary to insulate, for instance the actions taken by
the construction workers.

Second, to analyse the technical aspects, the systems and parts used to insulate dwellings are discussed in detail with data from the case study. In addition, a correlation matrix is created afterwards to identify the largest potential for efficiency gains within the technical design.

Third, relevant regulations, mainly determined by the international institutions (EU) and national (Dutch) government, are assessed. These are obtained with literature research. After that, it is important to analyse which part is critical to improve. In other words, the most time consuming problems will be considered. With an improvement on this element, the most time will be saved, which makes it possible to close the gap between supply and demand of the retrofitting industry.

4. Quantitative research on retrofitting

In the initial phase of the research method, a case study is carried out with the aforementioned area split. The observations are summarised in the key findings at the end of this chapter. The case study focuses on the roof renovations, therefore it excludes unrelated retrofitting elements. Due to the chosen research methodology, the observations will be addressed in a specific way and without ‘solution thinking’.

4.1. Process

A retrofit consists of everything from contracting to cleaning up the construction site. This research focuses on elements of the process that take place onsite, as this is where automated solutions are not already prevalent. The process includes gathering spatial data about the dwelling, transport of the insulation panel to the retrofitting site, placement of the panel, and finishing up the retrofitting. An overview of the entire process, as well as the planned days for execution, can be taken from Figure 1. The hierarchical order of the processes will also be maintained in the following elaboration of the individual items. The cleanup of the construction site is not taken into consideration because this is only the result of the preceding steps. The definition of the parts mentioned within the following process explanation is kept to the specific step where they are used primarily.

![Figure 1. Process steps and planning of the case study](image)

4.1.1. Data gathering. Initially, a point cloud is constructed with Light Detection and Ranging to capture accurate spatial data about the dwelling in a Building Information Model [14]. This model is used to determine the dimensions of the panels. Due to the limited possibilities of the scanning technology, only the outer parts of the dwelling could be modelled. In addition, no dynamic data is acquired that monitors activities, as will become clear in the description of the panel placement. As a result, issues occur during the preparation of the dwelling and placement of the panel.

4.1.2. Mounting preparation. To prepare a dwelling for retrofitting any obstacles must be cleared around it. Considering that the majority of Dutch terraced dwellings have fencing around them, this step can cause a significant lead time increase.
Scaffolding will then be placed next to the facade and above the entrance to the dwelling to allow work to be carried out on the roof and for safety reasons. The retrofitting uses a mounting system which spans the roof from the front to the back sides of the dwelling. This system is attached to the facade panels for alignment, and hinged at the ridge to carry downwards forces. The mounting system is placed above the load bearing walls (LBW), where the roof tiles and roof decking are previously removed. Any remaining space in between this bracket and the wall is filled with spacers to prevent sagging of the bracket. In addition, fire retardant material is added where the roof decking was removed, to comply with the regulations. The bracket is afterwards fixed to the purlins, which are in turn anchored to the LBW inside the dwelling to carry upwards forces. The lack of information about the position of the purlin and the low accuracy of the measurement led to several attempts for the fixing.

After that, an aerial working platform (AWP) and safety equipment enable the specially trained construction workers to reach the roof during the process of bracket installation. Regarding the significance of this study, it should be noted that more than half of the accidents in the construction industry are due to work at height [15].

4.1.3. Transport to site. The maximum width of cargo in the EU is limited to 2.55m [16]. This means that the smaller panels were transported flat on a truck, which is not always possible. Thus, wider roof panels were loaded onto an angled mount on the truck so they could be transported and lifted at the same orientation as the one they are in when mounted to the roof. The space available on the truck limits the number of panels that can be transported. In addition, the 6m length of the panels used caused difficulties when transporting them through the narrower streets.

4.1.4. Panel placement. With the placement, the roof panel is lifted with a telescopic crane mounted onto a truck. Specialised hooks have been tested that release automatically when the panel is attached to the mounting system. Unfortunately, this was unsuccessful due to an incompatibility with the panel. Moving the panel with the crane cannot prevent rotation around the vertical axis, so manual manipulation is necessary. This is one of the reasons why workers are needed on the roof, which leads to the use of scaffolding. Tilting the panel is also done manually with pulley chains to have the panel align with the slope of the roof. Precise positioning when the panel is near the bracket is again done by construction workers. The panel is placed on the bracket and slides down to lock mechanically and close the gap to the panel below. It proved time consuming to correctly position the panels sideways, which would be impossible if there were no workers on the roof.

4.1.5. Finishing. The remaining cavities between the panels are filled with polyurethane. Seams between the roof panel and facade panel are filled with expanding foam tape using the AWP. Furthermore, the gap between roof insulation panels of two different dwellings is covered with a metal sheet.

In case not all dwellings are retrofitted in a row, the face above the LBW separating a retrofitted and a not retrofitted dwelling has to be covered with additional material to ensure the energy performance of the retrofit.

4.2. Technical
As explained in the previous paragraph, retrofitting is complex with the variety and number of steps. In addition, such large processes create the risk for human error during execution [17, 18]. The technical parts of the used system that underlie this process are the insulation panel, its mounting system, and the lifting mechanism.
4.2.1. **Insulation panel.** The use of sandwich panels in the building sector is becoming more popular due to the energy efficiency in buildings [19]. Expanded polystyrene (EPS) is used for insulation and combined with metal sheeting for the structure of the panel [20]. This structure of the panel is crucial for how it can be transported and placed on the roof. The structural properties make it possible for the panel to span a length of 6m without the need for additional support. The width of the panel is limited to 3m as a larger panel will make the transport impossible. As a result, four panels were used to cover the whole roof. This creates a challenge to make the panels interlock, so the connection is resilient to environmental factors. However, the connection also means that a lot of follow-up work is required to make this connection airtight and watertight. This is difficult to execute since there is little room between the panels.

4.2.2. **Production.** The prefabricated panels are made from coated EPS that is glued between two metal sheets. This composition is kept under pressure utilising a vacuum during the drying of the glue. The width of a single panel is limited by the dimensions of the house, structural integrity, and possibilities for transport. The height is limited due to constraints in the mode of transport.

4.2.3. **Mounting system.** The mounting system is the connection between the insulation panel and the load bearing structure of a dwelling. The mounting system is characterised by hooks which are used to carry the weight of the panel and guide the movement during the alignment. However, they are designed with the human factor in mind, making them a time-consuming component during the mounting process. The placement of the panel is only as robust as the position of the mounting system is precise. In addition, the hooks are designed in such a way that they can deform if the plate is not properly aligned.

The attachment of the mounting system directly to the top of the LBW through drilling is known to compromise the structural integrity [21]. This is why it is attached to the purlins, and additional anchoring to the LBW is needed to secure the panel properly.

4.2.4. **Lifting mechanism.** The panel is lifted at four points where the connection with the mounting system is made, which was intended to trigger the automatic hook release mechanism described in paragraph 4.1.4. Additionally, a frame between the hooks and the crane tip distributes the forces appropriately and allows an easier alignment of the panel. Since the designed hook mechanism was not feasible with all panels, conventional lifting eyes and hooks were used in combination with the crane. They do, however, require human interaction for their attachment and detachment, contributing to the necessity for scaffolding.

4.3. **Regulations**

To ensure a future proof scalable retrofitting process, it must comply to international (EU) and national (Dutch) regulations. The regulations of the Netherlands comply with the EU guidelines and will thus be considered.

4.3.1. **Project.** By making Dutch dwellings more sustainable, a package of laws and regulations needs to be considered [22]. The focus of this research lies on the current building stock, and therefore the laws and regulations for new construction projects will not be discussed. For projects such as retrofitting it is crucial to comply with high level agreements such as the Building Decree [23], but also with agreements regarding the energy performance of the dwellings after renewal [24]. To increase the productivity of retrofitting in Europe, regulations need to be adapted to meet the objectives of governments.
4.3.2. **Process.** The process of retrofitting could lead to conflicts with old and new regulations. Thus, the process will require certain preparation before the dwelling is renewed [25]. The following regulations have a direct negative effect on the duration of the retrofitting process:

- complete and partial demolishing of the roof needs preliminary research, measurements, and inspection on instability [25];
- complete and partial demolishing of the roof needs research on asbestos [23];
- the retrofitting process building site (when using multiple machinery) needs to be drawn to scale in advance;
- during the realisation of the process, there must be provisions for emergency services [25];
- the noise during the retrofitting process needs to comply with the regulations [26];
- lifting systems and machinery can only do special maneuvers when it does not result in hindrance [25];
- during a retrofitting process the connection between two dwellings needs to be made fire retardant for at least 30 minutes in case of fire [27].

These points of interest result in time loss for the improved process and therefore need to be considered and adapted to make retrofitting more productive.

4.3.3. **Technical.** The technical solutions used in the retrofitting process are subject to individual regulations. For the technical parts and products the regulations are:

- for the mounting system is it crucial that the new innovative type of connection does not influence the bearing structure of the dwelling, and needs to keep the insulation panel in place [28];
- the material and composition of the insulation panel must meet all the medical and constructional conditions [25];
- the used lifting system in the process needs to be in line with the construction safety zone [25].

4.4. **Key findings**

Researching the three frameworks resulted in finding and understanding the drawbacks of the current retrofitting construction work in the Netherlands.

One of the most time consuming parts of the process is the assembly and disassembly of scaffolding, whilst this is needed for ensuring the safety of the construction workers and residents. The movement system of retrofitting panels has many movable components that require to be mounted before the lifting can be executed safely. Additionally, the panels are transported flat or angled, which enhances the complexity of lifting since roofs are commonly sloped. Furthermore, the lack of information for the panel placement on the roof causes alignment issues to occur often during the retrofitting process. These issues also cause a misalignment of the mounting system with the LBW, as well as the mounting system and insulation panel. The remedying of the alignment issues safes up most of the mounting process time. An increase of the lead time also occurs due to strict EU and Dutch regulations. Complying with the old and new regulations related to construction and energy performance requires preliminary research and verification. This is in contradiction to having a time efficient dwelling retrofitting process.

By removing any form of scaffolding from the retrofitting process, a significant impact can be made. By completely removing the time needed for preparing and utilizing scaffolding, the process step mounting preparation will be shortened and more productive.
5. **Opportunities to enhance productivity**

In this chapter, the possibilities for optimising the productivity of the retrofitting process are described. As explained in the previous part of the paper, these are categorised as a process, technical, and regulations. All possible solutions presented below are based on the data of the case study and literature research from Chapter 4. Finally, the correlations to the previously described key bottlenecks and the solutions contribute to the increase in productivity are shown.

5.1. **Process**

To ensure that the process is applicable for automated solutions, all products must be compatible with this concept. The panel lifting is the first part that is determined to be unfit for an automated process. By using a suction function for lifting the panels, known from the glass industry, no direct human interaction is needed anymore for the connecting, detaching, and orienting of the panel [29]. Also, to prepare the roof for automation, a low information density is required to operate robustly onsite. This can be done by changing the measurement method and system to get more detailed data about the location of the LBW and purlins.

5.2. **Technical**

The current design of the retrofitting product is made to be manipulated manually. As described in Paragraph 4.2, the system that is currently used requires anchoring of the purlins inside the dwelling, which can only be done by construction personnel. Additionally, automation of the attachment of the system to the purlins is not deemed feasible. Changing the design of the mounting system is necessary to accommodate automation.

A new mounting system is proposed that clamps on to the LBW, solely utilising friction to resist forces applied to the roof from environmental factors such as wind and rain. This would eliminate the need for manual procedures to take place on the roof or within the dwelling. The clamping mechanism would apply compression forces on the LBW. The initial force needed could be applied by a powered system or by leveraging the weight of the insulation panel, deflecting its gravitational force towards the LBW on both sides. A ratchet system could be used to maintain the clamping force.

An alternative for the clamp solution is found with a joined panel with hinges that is connected at the ridge of the roof. With this system, there are two insulation panels of 6 by 3m which are joined together by a hinge. By placing two of these folding panels next to each other, the entire roof can be covered with insulation [30].

The number of processes is decreased even further by integrating this system with the insulation panel, yielding a click on solution with the aforementioned clamp for roof insulation mounting. The design specifications of such a system are a topic for further research.

5.3. **Regulations**

As described in Paragraph 4.4, one of the key bottlenecks is the number of rules that retrofitting has to deal with. One possible solution to reduce the time spent on the laws is to store them together and centrally. A restructuring and specification to the retrofitting sector would provide clarity and efficiency in the regulatory application process. This must be communicated as an aim to the responsible political institutions to achieve higher productivity performance in the industry. Another possibility is the certification of companies, which would ensure the process approach and its quality [31]. This could eliminate the obligation to apply for permits, as a company can prove that it is certified and thus guarantee compliance with the guidelines.

5.4. **Correlations**

To clarify the connections between the key bottlenecks and the opportunities, a correlation matrix is
shown in Figure 2. Here we can see that the correlation with the highest score is between opportunity 1 and 3. The demand and focus for future research projects can therefore be specifically placed to ensure a productive future for retrofitting in Europe. After working on opportunities 1 and 3, opportunities 4, 5 and 6 should be pursued to ensure the best possible contribution to increasing the productivity of the retrofitting process.

| OPPORTUNITIES | 1. Assembly and disassembly of scaffolding | 2. Conventional movement system | 3. Flat or angled panel transport | 4. Lack of information for mounting | 5. High amount of regulations (EU & Dutch) | 6. Decentral source for regulations | Total score |
|---------------|------------------------------------------|---------------------------------|-------------------------------|---------------------------------|----------------------------------------|----------------|------------|
| Suction system for panel movement | 1 | 1 | 1 | 1 | 0 | 0 | 3 |
| New and precise measurement system | 2 | 0 | 0 | 0 | 1 | 0 | 1 |
| New clamp design for connection to LBW | 3 | 0 | 1 | 0 | 1 | 0 | 2 |
| Merge between mounting system and panel | 4 | 1 | 1 | 0 | 0 | 0 | 2 |
| Centralised source for retrofitting regulations | 5 | 0 | 0 | 0 | 0 | 1 | 1 | 2 |
| Certification retrofitting processes | 6 | 0 | 0 | 0 | 0 | 1 | 1 | 2 |

Figure 2: Correlation matrix with the connection between opportunities and key bottlenecks

6. Discussion

This research was approached from an engineering perspective. This must be addressed as a risk because it excludes viewpoints from other fields of experience. By working with people from other relevant fields, this could be prevented and greater objectivity could be achieved.

In addition, the fact that only one specific type of dwelling has been studied has to be taken into account. To increase the productivity of retrofitting all over Europe, the diversity of dwellings must also be respected. Different styles and types of construction are followed in each country of the EU, resulting in the requirement for a very adaptable system. This constraint has not been considered in this research.

The examination of optimisation in terms of lifetime and durability is also not taken into account. The given solutions must be subjected to long term testing to prove their suitability for field use. It is therefore difficult to say whether the panels meet the criteria of building physics. The roof panels are made from EPS, which is produced with petrochemicals. This makes it an unsustainable solution and it should be investigated whether a more natural alternative material can be used.

In addition, the use of robots goes hand in hand with future legislation. It must be considered that the occupants are exposed to completely new threats, thus also requiring specific protection. The area of use and the corresponding safety precautions should not be neglected.

With the use of robots on the construction site, the question of the legal framework comes up. Additional research must be conducted to determine whether the necessary basis is given to answer possible liability questions.
7. Conclusion

It is clear that action must be taken within the construction industry since residential and non residential buildings are responsible for 27% of the total CO₂ emissions worldwide [2]. To reduce these emissions, the number of retrofitted dwellings must increase.

The process of roof installation could be shortened and scalability increased by developing robotised construction solutions, adapting product design to automated processes that require less manual labor, and easing regulations. A robotised crane movement based on data collected during process preparation would result in a reduction in construction lead time. Following that, the adapted product design with a mechanical self attaching mechanism that does not require manual labor will eliminate the need for people on the roof and thus the scaffolding. At the very least, construction site regulations and the aforementioned suggestions must be consistent in order to ensure project owners dependability and construction workers safety.

On the basis of the stated key results, a project should be carried out on a physical scale. It is clear that the findings of this research project can be verified by measuring the process indicators in the context of a small scale model. With the outcomes of the proposed further research, the reduction of CO₂ emissions in the construction industry could be reduced.

References

[1] Arias P, Bellouin N, Coppola E, Jones R, Krinner G, Marotzke J, Naik V, Palmer M, Plattner G K, Rogelj J et al. 2021 Sixth Assessment Report of the Intergovernmental Panel on Climate Change 6

[2] United Nations Environment Programme 2021 2021 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector URL https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction

[3] Eurostat 2021 Final energy consumption in the residential sector by use, eu URL https://ec.europa.eu/eurostat/statisticsexplained/index.php?title=Final_energy_consumption_in_the_residential_sector_by_use_EU_2019_F2.png

[4] Directorate-General for Energy European Commission 2020 A renovation wave for europe - greening our buildings, creating jobs, improving lives URL https://ec.europa.eu/energy/sites/ener/files/eu_renovation_wave_strategy.pdf

[5] El-Darwish I and Gomaa M 2017 Alexandria Engineering Journal 56 579–589 used pages [p.579-589]

[6] Directive E E 2012 Official Journal, L 315 1–56 used pages [p. 1-56]

[7] Ministerie van Economische Zaken en Klimaat 2019 Klimaatakkoord URL https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord

[8] Vrijhoef R 2016 Effects of lean work organization and industrialization on workflow and productive time in housing renovation projects (Proceedings of the 24th Annual Conference of the International Group for Lean Construction) used pages [p. 63-72]

[9] Koskela L et al. 1992 Application of the new production philosophy to construction 72nd ed (Citeeseer) [10]Botero J C, Djankov S, Porta R L, Lopez-de Silanes F and Shleifer A 2004 The Quarterly Journal of Economics 119 1339–1382 used pages [p. 1339-1382]

[10] Botero J C, Djankov S, Porta R L, Lopez-de Silanes F and Shleifer A 2004 The Quarterly Journal of Economics 119 1339–1382 used pages [p. 1339-1382]

[11] Loera I, Espinosa G, Enríquez C and Rodriguez J 2013 Procedia Engineering 63 947–955 used pages [p. 947-955]

[12] Kumar V, Prasanthi I and Leena A 2008 Proceedings of the AIE 2008 Conference - AIE 2008: Building Integration Solutions 328 1–9 used pages [p. 1-9]

[13] Benavides E M 2012 Advanced engineering design - An integrated approach (Woodhead Publishing) [14]Palleja T, Tresanchez M, Teixido M, Sanz R, Rosell J and Palacin J 2010 Agricultural and Forest Meteorology 150 1420–1427 used pages [p. 1420-1427]

[14] Palleja T, Tresanchez M, Teixido M, Sanz R, Rosell J and Palacin J 2010 Agricultural and Forest Meteorology

[15] De Bouw Maakt Het 2022 Laat veiligheid niet vallen URL https://veilig.debouwmaakhet.nl/op-hoogte/ vallen
[16] International Transport Form 2012 Permissible maximum dimensions of trucks in europe URL http://www.interim-xl.de/cv/dimensions-road-transport-europa.pdf

[17] Atkinson A 1998 Construction Management and Economics 16 339–349 used pages [p. 339-456] [18]Grabowski M and Roberts K 1996 IEEE Transactions on Systems, Man, and Cybernetics - Part A Systems and Humans 26 2–16 used pages [p. 2-16]

[18] A Grabowski M and Roberts K 1996 IEEE Transactions on Systems, Man, and Cybernetics - Part A Systems and Humans 26 2–16 used pages [p. 2-16]

[19] Briscoe C R, Mantell S C, Davidson J H and Okazaki T 2011 Journal of Sandwich Structures & Materials 13 23–58 used pages [p. 23-58]

[20] Pan P, He Z Z, Wang H and Kang Y 2022 Engineering Structures 250

[21] Segura J, Pelé L, Roca P and Cabané A 2019 Construction and Building Materials 228

[22] Rijksdienst 2022 Wetten en regels gebouwen | rvo.nl | rijksdienst URL https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels

[23] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties 2012 Bouwbesluit 2012, article 1.26 | bouwbesluit 2012 URL https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012

[24] Rijksdienst 2021 Energy performance of buildings directive (epbd iii) URL https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/gebouwen/wetten-en-regels/nieuwbouw/epbd-iii

[25] Vereniging Bouw- & Woningtoezicht Nederland 2018 Landelijke richtlijn bouw- en sloopveiligheid URL https://www.bwtnl.nl/upload/ckfinder/files/Sloop/Landelijke%20Richtlijn%20Bouw-%20Sloop%20versie%2009%20%202018.pdf

[26] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties 2012 Bouwbesluit 2012, article 8.3 | bouwbesluit 2012 URL https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012

[27] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties 2022 Afdeling 2.10. beperking van uitbreiding van brand | bouwbesluit online URL https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012/afd2-10

[28] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties 2021 Hoofdstuk 2 technische bouwvoorschriften uit het oogpunt van veiligheid, article 2.15 | bouwbesluit 2012 URL https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012_nvt/artikelsgewijs/hfd2

[29] Jaiswal A and Kumar B 2017 Int. J. Innov. Sci. Eng. Technol 4 187–194

[30] VolkerWessels 2015 VolkerWessels Renovatie in een dag URL https://www.youtube.com/watch?v=I3WBT2eAArI

[31] Ofori G and Gang G 2001 Engineering, Construction and Architectural Management