Comparison of Seismic Retrofitting Techniques

Exploring alternative techniques for strengthening buildings in Groningen

Bachelor thesis

Final version

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Preface

This research project has been written to fulfill the graduation requirements of the Bachelor Civil Engineering at the University of Twente. The research has been written over 10 weeks, from April until June. The research was executed at the request of Arcadis, in particular the earthquake department located in Assen, the Netherlands.

I would like to thank my supervisors for guiding me through this process. Furthermore, I would like to thank the participants in my interviews who helped with providing useful information to execute this thesis.

Summary

The goal of this research is to find an improved design of the wall-floor connections in the Groninger earthquake area because the current strengthening measures are extensive, expensive and cause nuisance for the inhabitants. The report aims to answer the following question:

> Which recommendations can be made after comparing the quality of different alternative designs for the wall-floor connections in the Groningen region?

This question will be answered with the use of the following 4 sub-questions. Below, the answer to each of the sub-questions will be given. Lastly, the main research question will be answered, which directly serves as the conclusion of this summary.

1. Which criteria are relevant for assessing the value of wall-floor connections?

The relevant criteria for the assessment are mainly composed with the use of stakeholder interviews. In these interviews, stakeholders were asked what their demands were for a strengthening measure. These answers were summarized into five general criteria. Afterward, the stakeholders were asked to prioritize their earlier mentioned criteria. This was the basis for composing the weight of each of the criteria. The exact weight of the criteria was based on a scoring system. Every time a criterion was mentioned, it received one point. During the prioritization task, stakeholders implicitly graded their criteria between 0 and 1. The most important criterion received one point, and the least important criterion received zero points. For criteria in between, the score was based on interpolation. The final score of the criteria was determined by dividing the score per criterion by the total amount of points given. This resulted in the following final criteria together with their weight:

Criterion	**Score:**
Quality	0.33
Feasibility	0.25
Minimizes nuisance	0.18
Costs	0.13
Aesthetics	0.12

2. Which alternative wall-floor connections will be evaluated?

The alternative connections that are evaluated are all found through literature and were selected based on whether they could be applied to existing houses. The list of evaluated wall-floor connections can be found in Chapter 5.

3. What is the quality of the different wall-floor connections given the assessment criteria?

In the Table below, the outcome of the multi-criteria analysis can be found. The scores were based on the relative score between each of the alternatives. A score of one point means that this alternative was best for this criterion, and a score of zero points means that the alternative was best.

Table 1: Outcome of the multi-criteria analysis

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics	Performance score	Rank
Weight	0.33	0.25	0.18	0.13	0.12		
Alt 1	0.47	0.55	0.83	0.94	0.95	0.19	6
Alt 2	0.89	0.72	0.83	0.84	0.81	0.37	4
Alt 3	**1**	**1**	**0.92**	**0.94**	**0.98**	**0.85**	**1**
Alt 4	0.67	0.86	0.65	0.94	0.91	0.32	5
Alt 5	0.80	0.95	0.96	1	1	0.73	2
Alt 6	1	0.86	1	0.73	0.81	0.51	3

4. What do we learn by comparing the quality of the alternatives according to the assessment criteria to make recommendations on how to proceed with strengthening houses?

As can be seen in Table 1, alternative 3 is the most suitable alternative. This connection is an L-shaped steel profile, which is anchored into the cavity wall with a T-shaped anchor. The main disadvantage of this alternative is that there is a bolt head on the insight of the building, which is difficult to properly finish off with carpentry. Moreover, when there is no cavity wall, this alternative is visible from the outside of the building. Therefore, an improved design has been made by van Engelen (2021). Instead of an anchor with a bolt head, this steel strip is connected to the masonry with a diagonal screw. This way, the connection can be easily finished off and is also applicable for buildings that do not have a cavity wall.

While these designs are both promising, it should be further researched to see whether the connections meet the design requirements from the NPR 9998.

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1. Introduction

Earthquakes in Groningen are often subject to discussion. The earthquakes occur in the north-eastern part of the province and are caused by gas extraction of the underlying Groningen gas field. This field is located approximately 3 km beneath the earth's surface. Natural earthquakes of this intensity are rather unique in the country. It was only since the earthquakes in Groningen began to occur because of large-scale gas extraction, that the Dutch building industry had to be concerned with seismic activity on the buildings. The existing buildings in the region were not designed to withstand seismic activity, which makes them vulnerable to earthquakes. According to Vlek (2018), earthquake damage affects 600 000 inhabitants. Two of the biggest concerns of the inhabitants are further damage to buildings and a decreased value of their property (Vlek, 2019).

To make sure the existing buildings are strong enough to withstand the earthquakes, the buildings are retrofitted. Retrofitting is the addition of new technology to an existing structure to make them more resistant. Mostly, the technique used for retrofitting buildings in earthquake regions is strengthening the components of the building.

In this research, I will look for a new method of strengthening houses in the Groningen region that causes less hinder to the inhabitants. The focus will be on the connection between masonry walls and timber floors, as most existing houses in the area are built like this. The decreasing chance of heavy earthquakes due to the reduction of gas extraction of the Groningen gas field (KNMI, 2018) will also be considered. The research area is North-East Groningen, the area above the Groninger gas field. In Figure 1, the research area is indicated with the orange line. The research focuses on the years 2021-2030, but the period afterward will also be considered. This period is chosen because, in 2030, the government plans to stop the extraction of gas in Groningen. It should be noted that after 2030, earthquakes might still occur, but the chance of a heavy earthquake will become smaller (KNMI, 2018). Therefore, the period after 2030 is also considered, but not focused on.

Figure 1: Research area, indicated with the orange line (ARUP, 2013)

First, the problem statement and objective will be explained. Next, the research questions that need to be answered to achieve the objective will be described. Afterward, literature research will be performed into the technical background and the position of stakeholders. Inhabitants and experts will be interviewed to set up relevant criteria. These criteria will then be used to perform a multi-criteria analysis on 6 different alternative wall-floor connections. These connections were found in literature. The multi-criteria analysis will be the basis of the recommendation that will be performed at the end of this report.

1.1. Problem statement

The total work stock of Nationaal Coordinator Groningen (NCG) consists nearly out of 27 thousand addresses, for which currently only 7% the strengthening measures have been concluded (NCG, 2021). This shows that the strengthening process is lengthy. The Dutch state supervision on mining, SodM, warns for unnecessary delays in the strengthening phase. Thus, the method of strengthening requires an improvement so it can be implemented quicker.

To implement the current way of strengthening the wall-floor connection, the ceiling must be removed. This causes nuisance for the inhabitants of the building. Inhabitants temporarily need to move out of the building, and the furniture needs to be moved from the story beneath the ceiling. The paintwork on beams and ceilings can also be damaged. In some cases, the strengthening measures require space inside the building, which decreases the living area of the inhabitants. The inhabitants suffer from these strengthening measures, but also suffer when there is earthquake damage to their house. Since the chance of a heavy earthquake is decreasing, less invasive strengthening measures need to be applied compared to the previous situation. Therefore, it is necessary to find a way in which houses can be strengthened quicker, with less nuisance to the inhabitants.

Van de Graaf & Hoppe (1989) made a distinction between different types of problems. The problem as described before is an untamed technical problem. This means that it is agreed upon by stakeholders that the problem needs to be solved, but there are no technical solutions available yet (van de Graaf & Hoppe, 1989). In this case, there are technical solutions available, but they could be improved.

1.2. Objective

The objective of this research is to find an improved design for the wall-floor connections in masonry houses in the Groningen region. This will be done by comparing different alternative designs in order to make a recommendation of which design suits the situation in Groningen best. To explore what an "improved" design means, an objective tree has been made. This objective tree can be found in Figure 2. As can be seen, the objective is to find a wall-floor connection that is aesthetically pleasing and causes less nuisance for inhabitants, without being more expensive and that has sufficient capacity.

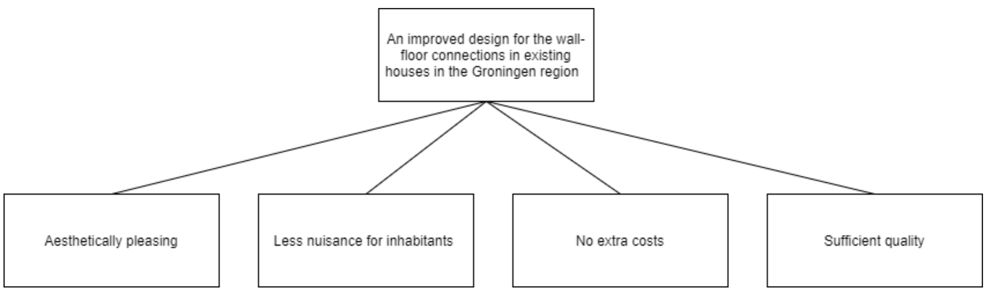


Figure 2: Objective Tree

1.3. Research question

In this paragraph, the main research question will be discussed together with its sub-questions. In total 3 sub-questions will be used to arrive at the research objective. Two of the sub-questions are again divided into sub-questions. The main research question is:

> **Which recommendations can be made after comparing the quality of different alternative designs for the wall-floor connections in the Groningen region?**

This question will be answered with the use of 4 sub-questions.

1. Which criteria are relevant for assessing the value of wall-floor connections?
   1.1. Who are the stakeholders?
   1.2. Which criteria can be derived from the stakeholder analysis?
   1.3. Which criteria can be derived from the technical requirements?
   1.4. Which criteria can be formulated as a mutual confrontation of 1.2. and 1.3?
   1.5. What is the importance of each of the criteria?
2. Which alternative wall-floor connections will be evaluated?
   2.1. How are the different alternatives found (e.g., literature, own design, etc.)?
   2.2. What are suitable alternatives for the given situation?
3. What is the quality of the different wall-floor connections given the assessment criteria?
   3.1. How do the alternatives score on the assessment criteria?
   3.2. Why do the alternatives score in a certain way on the assessment criteria?
4. What do we learn by comparing the quality of the alternatives according to the assessment criteria to make recommendations on how to proceed with strengthening houses?

2. Set-up of the research

In this chapter, the set-up of the research will be elucidated. The research aims to answer the research questions, and thus to meet the objective: to find a wall-floor connection that is easier to implement for construction workers and causes less nuisance for inhabitants, without being more expensive and with sufficient capacity.

2.1. Literature research

As a starting point, literature research has been done. This literature research aimed to gather more insight into the effect of earthquakes on houses, the gravity of the situation in Groningen, and the parties involved. Also, the alternative connections that will be compared are found through literature research. This research can be seen as the starting point of the research project. The most relevant findings can be found in Chapter 3, and a description of the alternative connections can be found in Chapter 5.

2.2. Stakeholder analysis

In the literature research, research was done, among other things, to the parties involved. To get an even better idea, a stakeholder analysis has been performed. The goal of this analysis was to get insight into the objectives of each of the stakeholders. To perform this analysis, literature research has been done. On top of that, experts and inhabitants were asked about their problem perception, objectives, and demands. Moreover, during the expert interviews, some experts were asked to name the most important stakeholders involved in this project.

2.3. Interviews with inhabitants and construction companies

Inhabitants are the most important stakeholders during this research since they are the ones that must accept the chosen alternative in their houses. Therefore, the inhabitants have been interviewed to examine their demands and wishes. Each of these inhabitants lives in the earthquake region because they are generally familiar with the topic. Construction companies have been interviewed because they have much knowledge about the execution of strengthening houses. Moreover, they might have a more practical view compared to the structural engineers who will be discussed later. Other important stakeholders, such as the municipality and the NCG, have also been contacted but unfortunately did not respond.

2.3.1. Method

The method used for these interviews was a structured interview. This was chosen to give inhabitants structure and clarity of the interview. The interview was performed one-on-one over the telephone.

2.3.2. Amount of interviews

The aim was to find as many inhabitants as possible, to get the most significant result. Unfortunately, these inhabitants were difficult to find. Eventually, four inhabitants have been interviewed. Most inhabitants are homeowners, one is a tenant. Every inhabitant lives in the research area.

According to de Leeuw (2020), there are six construction companies involved in the strengthening industry in Groningen. Each of these construction companies has been approached. Out of these six companies, two companies responded, which also participated in the interview.

2.3.3. Diversity in answers

Since the number of inhabitants and construction companies is not enough to get a significant result, it is expected that there will be diversity in the answers. It is aimed to find a solution that pleases as many people as possible, therefore each answer, provided it is relevant, will be considered equally important.

2.3.4. Questions

First, an introduction will be given about the subject of the research to prevent misconceptions. Afterward, the scope of the research is explained, which is to research what demands the stakeholders have. In total, two questions are asked. The first question asks about which criteria they think highly of. Secondly, the person is asked to choose between two of the criteria this person mentioned. For example, a person mentions, among others, to want a solution that is beautiful and quick. This person then must choose which one would win if they were put against each other. As a result, a prioritization list of the different criteria can be made. The full results of the interviews can be found in Appendix B: Inhabitant interviews and Appendix C: Construction company interviews.

2.4. Expert interviews

To get more insight into the technical features of the designs, expert interviews are held with structural engineers from Arcadis. Moreover, the interviews are used to ask experts about criteria, problem perception, and possible solutions. These interviews differ from the inhabitants and construction company interview because these structural engineers are involved with the NCG, their client, the inhabitants, and the construction companies, and therefore have a good overview of the situation.

2.4.1. Method

The method used for the expert elicitation is a semi-structured interview. This method is chosen because it will give consensus on the problem perception and the criteria of the research project, as will it reflect the opinions of the experts on the alternative designs. To get answers in a specific direction, the structure is required in the interview. However, there is also room for the own interpretation and contribution of the experts. Therefore, a semi-structured interview has been chosen. The interviews will be held online, during a one-on-one session with the expert. The designs that will be compared have been sent beforehand, so experts have a slight idea of the kind of designs they must assess. This will save time during the interview. After the interview, the experts are asked to grade the alternatives based on the criteria. This must be done afterward since the criteria from the inhabitant interviews and the expert elicitation need to be combined.

2.4.2. Amount of experts

In the beginning, it was aimed to interview an average of five structural engineers, with a deviation of ±2 persons. At the inhabitant interviews, it was mentioned that more interviewees would mean a more significant result. Of course, this also holds for the expert interview. However, because the expert interviews took longer, they were more difficult to schedule, and therefore it was not realistic to interview as many persons. Moreover, the number of experts working on the earthquake project at Arcadis is limited. Both junior and senior structural engineers have been interviewed. This is chosen to have a broad range of working experience during the research.

2.4.3. Diversity in answers

It is the task of the interviewer to ask critically about the argumentation behind the answers of the expert. When there is substantial diversity in answers, the interviewer can evaluate the answers based on the quality of the argumentation. Also, the working experience of the expert needs to be considered. One can imagine that an expert in a senior function has a better understanding of the practical executability of a certain design since this expert has more working experience. On the other hand, a junior expert may be more open to ambitious, new ideas.

2.4.4. Questions

The questions asked during the interviews firstly aim at finding the problem perception of the expert. Next, the expert is asked which criteria are valued as important. Finally, the expert will assess the chosen alternatives discussed in Chapter 5.2. The questions asked during the interviews can be found in Appendix D: Interview questions for structural engineers. The complete answers to the questions can be found in Appendix E: Results interviews with structural engineers. The questions are aimed to be asked in the most general way possible, so the interviewer gets an idea of the priorities of the expert. Only open questions are asked to not direct the person in a certain direction. For the same reason, no suggestive answers will be mentioned by the interviewer.

3. Theoretical background

3.1. Earthquakes in Groningen

The earthquakes in Groningen are induced earthquakes, which means that they are caused by human activities. They occur because of long-term gas extraction in the Groningen region. Gas is located in the pores of the rocks, preserved under natural pressure (National Research Council, 2013). The extraction of the gas resolves into a pressure drop, which is, since the start of the production, on average approximately 22 MPa, which directly causes an increase of the effective normal stress, which then results in direct clamping of the rock (Candela et al., 2019). According to Candela et al. (2019), the pressure drop also leads to a contraction of the reservoir and a reduction of the horizontal stress. The reduction of the horizontal stress partially counteracts the earlier mentioned clamping. Because the vertical stress is unaffected, the shear stresses increase along with the nearly vertical fields, which will continue as long as the pore pressure decreases in the Groningen field (Candela et al., 2019). According to Vlek (2019), the seismic activity per unit gas extracted has increased, which means that the relative magnitude of the earthquake is larger.

As a reference, out of 90 earthquakes in the Netherlands in 2020, 69 of them were induced earthquakes caused by gas extraction (KNMI, 2021). The heaviest earthquake that occurred in Groningen happened in 2012 and had a magnitude of 3.6 on Richter's scale (KNMI, 2021). The Richter's scale measures the amount of energy released during an earthquake. This is the most well-known indicator of moderate-sized earthquakes but might not be the most appropriate one for the Groningen region. According to Rafferty (2020), an earthquake with a magnitude level between 3.0 and 3.9 is a minor earthquake. It is felt by many people, but there is no damage. The reason that the earthquakes in Groningen are more severe than indicated with Richter's scale, is that the distance between the hypocentre and the epicenter is small. In other words, earthquakes happen close to the earth's surface, which causes a higher intensity. This higher intensity can be measured with the Mercalli scale or with the Peak Ground Acceleration (PGA). In this project, the focus will be on the PGA.

The PGA is the maximum acceleration of the ground in m/s^2 or g-force g ($9.81\ m/s^2 = 1\ g$). In Figure 3 and Figure 4, the PGA in the Groningen region is illustrated for 3 different scenarios, in 2 different periods (2020-2023 and 2023-2027 resp.). The exceedance chance of the maximum PGA is 1 in 475 years (KNMI, 2018). The figures show that a decrease in acceleration between the different periods is predicted. As mentioned before, this is expected because of the decrease in gas extraction in the Groningen region. The decrease in gas extraction does not mean that the earthquakes will stop occurring, but the probability of a heavy earthquake decreases (KNMI, 2018).

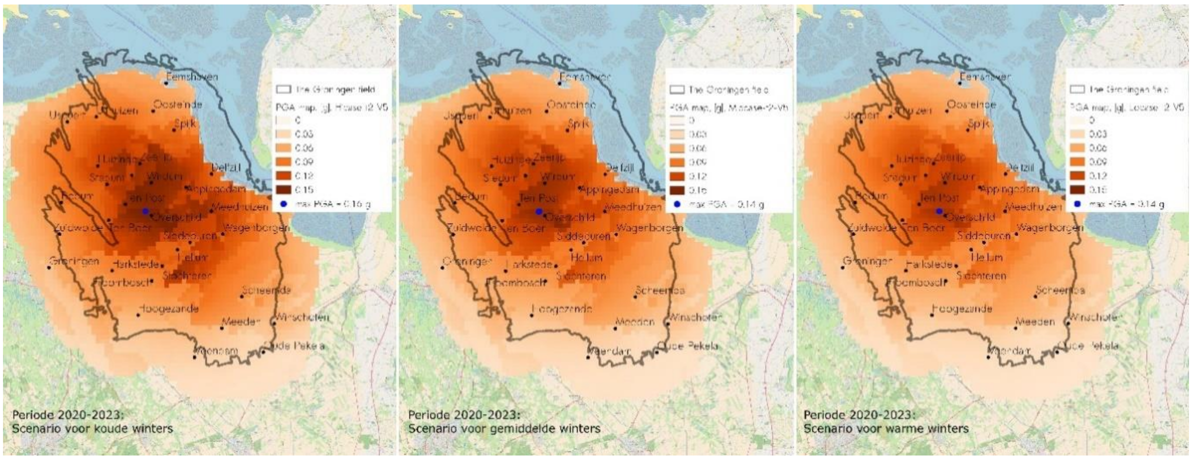


Figure 3: Hazard map for PGA in the period from 2020-2023. Scenarios for cold winters (left), average winters (middle), and warm winters (right) (KNMI, 2018)

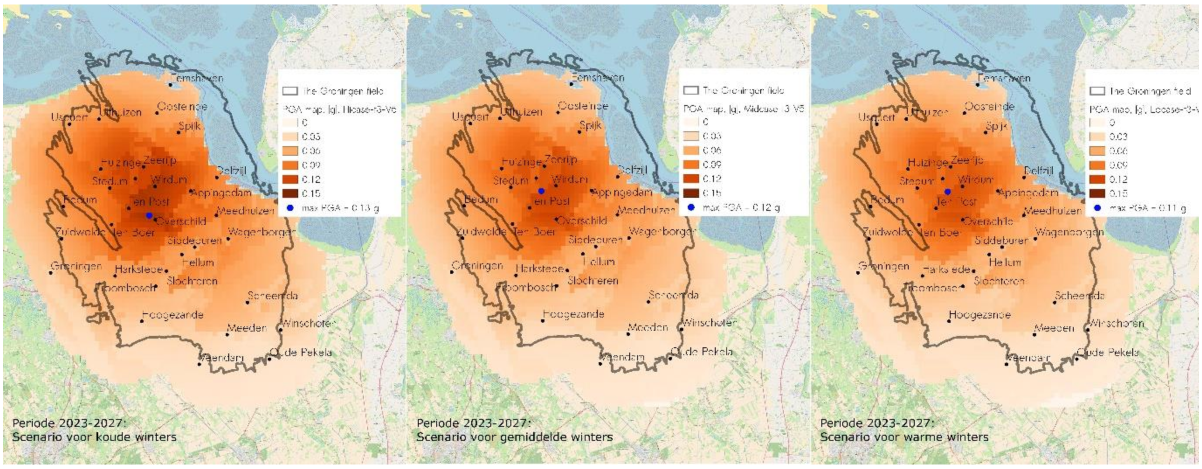


Figure 4: Hazard map for PGA in the period from 2023-2027. Scenarios for cold winters (left), average winters (middle), and warm winters (right) (KNMI, 2018)

3.2. Effect of earthquakes on houses

As mentioned before, earthquakes cause acceleration on the earth's surface. This acceleration is both vertical and horizontal. The horizontal acceleration has the most impact on the house. This horizontal acceleration combined with the mass of the house causes a horizontal force. Therefore, a decrease in the PGA or mass means a decrease in the horizontal forces on the houses. When most of the houses in Groningen were built, no seismic activity was expected. Many houses were already built before the gas extraction even began. Therefore, the houses were only expected to take up gravitational forces, and forces due to natural loadings, such as wind and snow load. Consequently, the houses are bad at resisting the horizontal forces caused by seismic activity.

3.2.1. Earthquake forces on masonry

In Groningen, most buildings are built from unreinforced masonry (URM) (Arup, 2013). Masonry is popular because of its compressive strength, but it is not very strong in shear load, like during an earthquake. Masonry consists of bricks and mortar. The quality of both the bricks and the mortar is diverse. In Groningen, most of the time the mortar is the problem. URM is a brittle material, which means that there is no warning before it fails. This makes it a dangerous material during earthquakes.

The performance of masonry walls differs with the direction of the seismic activity. The accelerated ground and the mass of the wall cause a force in the opposite direction of the acceleration. In in-plane acceleration, the walls are relatively strong. The walls that are perpendicular to the direction of the earthquake shaking are called transverse walls. These walls are typically weaker than shear walls. The masonry will bend or topple, depending on the vertical forces. An illustration of the effect of in-plane and out-of-plane seismic activity can be seen in Figure 5.

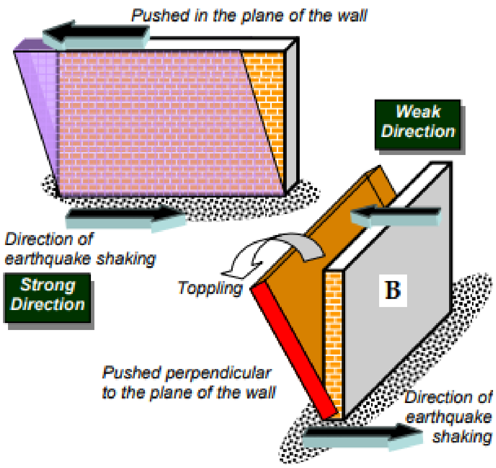


Figure 5: Effect of in-plane and out of plane seismic activity on masonry walls (IITK, n.d.)

The stability of the building during and after an earthquake is mainly caused by the walls loaded in the in-plane direction.

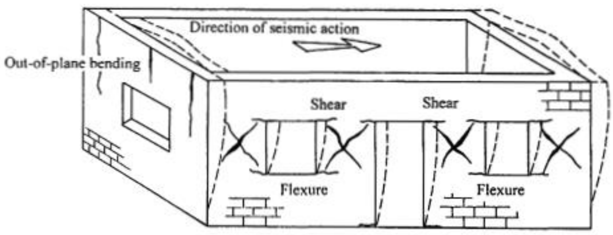


Figure 6: Deformation of a masonry building and typical damage to a structural wall (Tomazevic, 1999)

Of course, in a building, the walls are connected and work together. Figure 6 shows the deformation of a simple masonry building. This figure also shows a typical damage pattern. However, when the elements are not connected, each element vibrates on its own (Tomazevevic, 1999), which increases the chance of damage and/or failure. Tomazevic (1999) states “The seismic performance of an unreinforced masonry building depends on how well the walls are tied together and anchored to the floor and the roof.”

According to Arup (2013), walls falling out-of-plane is one of the most common structural failures in masonry buildings. This happens especially in case of bad connections to the floors and the roof. The transverse walls move away from the floors and roof, which could cause them to topple and fall out-of-plane (Bothara & Brzev, 2011). This is illustrated in Figure 7. When the structure is unified with the means of proper connections, the inertia forces, which are generated by the vibration of the house, can be transmitted to the members that can resist them (Arya et al., 2014). The transverse walls find stability through the shear walls. According to Arya et al. (2014), the most important elements to connect are the walls with the floors/roof, walls and foundation, and connecting intersecting walls. In this research, the focus will be on the wall-to-floor connections.

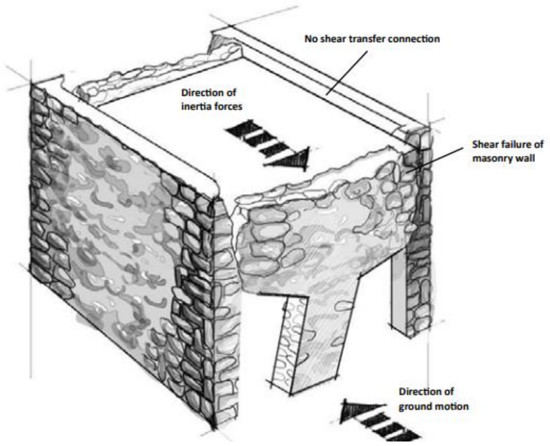


Figure 7: Failure due to inadequate wall-floor connection (Bothara & Brzev, 2011)

3.2.2. Strengthening measures

Up until now, the only method for strengthening that has been mentioned is the increased wall-floor connections. While this is the most measure in this research, it is also important to understand the other measures that can be taken. The focus will be on permanent measures. According to Arup (2013), there are 7 intervention levels with increasing complexity, duration, and impact on inhabitants. The intervention levels are:

1. Mitigation measures for higher risk building elements (removing potential falling hazards)
2. Connecting the floors and walls
3. Stiffening of flexible diaphragms
4. Strengthening of existing walls
5. Replacement and addition of walls
6. Strengthening of the foundation
7. Demolition

As it can be seen, tying the walls to the floors is one of the first intervention levels. This means that the complexity, duration, and impact on inhabitants are relatively low. Since the chance of a heavy earthquake is decreasing, it is important to research less invasive measures, such as level 2 measures.

4. Stakeholder analysis

In Appendix A: Stakeholder table, an overview of the interest, objective, and existing/expected gap of each stakeholder can be found. Most stakeholders would benefit from roughly the same possible solution: a design of the wall-floor connections that is quicker, cheaper, and causes less nuisance. Of course, this would not be an option for houses where more extreme strengthening measures are required, but it would be helpful for houses for which only the level 2 measure is required. A solution for the problem could be a general strengthening measure for a group of similar houses. This way, the plan of approach is quick and only a few calculations need to be made, which makes the solution cheap. While inhabitants would benefit from a quick solution, they might not feel safe under this solution and would prefer an individual assessment and calculation for their house. Moreover, these strengthening measures might be more extensive and stronger than necessary.

4.1. Interviews

In addition to the stakeholder analysis, multiple parties have been interviewed to get a better comprehension of their demands for a new solution. Inhabitants, construction companies, and structural engineers were asked to prioritize the criteria they thought were important to them. A lot of the criteria that were mentioned have an overlay. For example, durability and quality. When a connection is of good quality, you would expect it to be durable as well. Therefore, the criteria were summarized in more general criteria. In Figure 8, an overview of the general criteria can be seen, and the criteria they were put together from. The colours of the 'small' criteria represent the party that mentioned them. When a criterion is mentioned by multiple parties, this is a general criterion that every party interviewed is invested in. This criterion is then also showed multiple times in the figure, to show that it was mentioned by multiple parties.

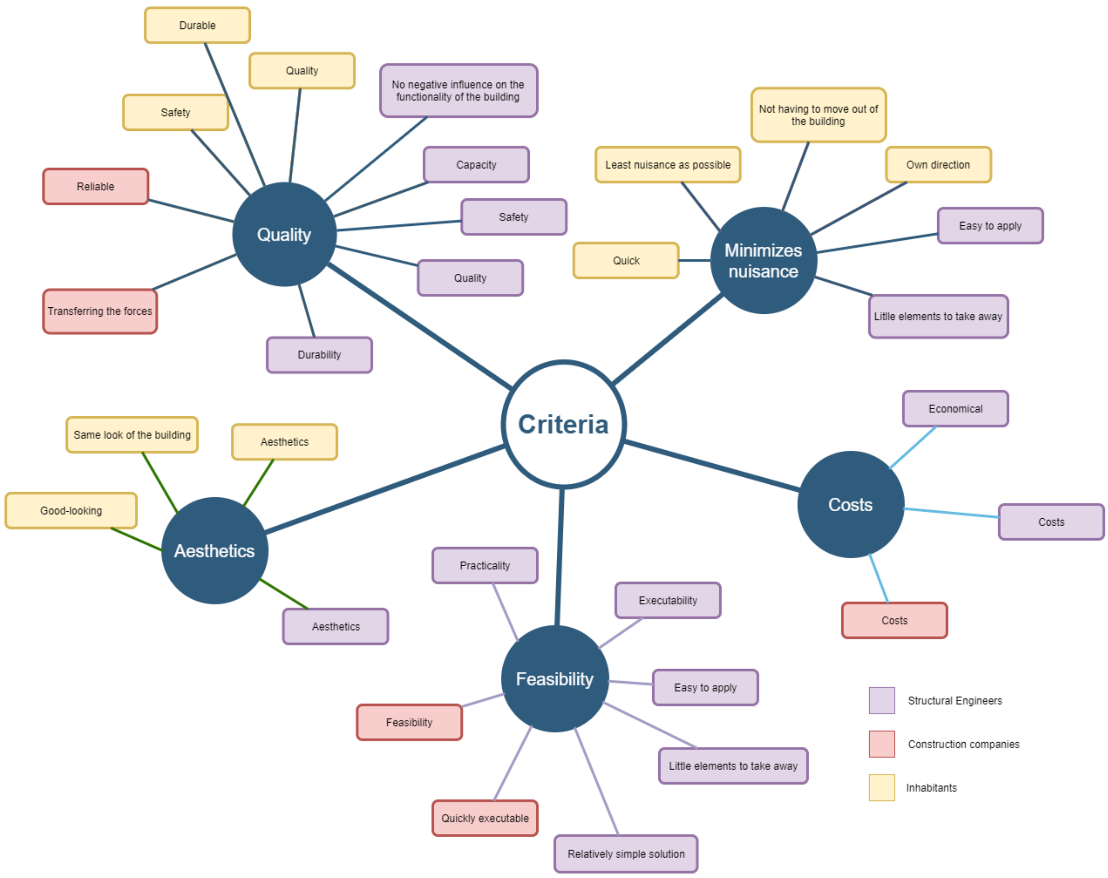


Figure 8: Diagram of the different criteria mentioned by the stakeholders

As can be seen in Figure 8, there are five main criteria that will be considered. These criteria are:

- **Quality**: To what extent is the design capable of resisting the forces during seismic activity?
- **Minimizes nuisance**: How much nuisance is caused by the alternative? For example, is the implementation time-consuming? Do inhabitants have to move out of their house?
- **Aesthetics**: What is the aesthetic impact of the design on the house?
- **Feasibility**: How likely is it that the design will be implemented? For example, is it practical to execute?
- **Costs**: What are the costs of the implementation and materials of the design?

Besides this, the criteria mentioned by the stakeholders are also assessed with a scoring system. The inhabitants were asked to prioritize their earlier mentioned criteria. Every time a criterion was mentioned by one of the stakeholders, it received one point. On top of that point came the points from the prioritization, between 0 and 1. Afterwards, the score is normalized so that the sum of the scores is equal to one. This is required to perform the multi-criteria analysis with the weighted product method, which will be elaborated further in Chapter 6. The results from the scoring system can be seen in Table 2. The complete answers from the stakeholder interviews can be found in Appendix B: Inhabitant interviews, Appendix C: Construction company interviews, and Appendix E: Results interviews with structural engineers.

Table 2: Final criteria with their weight

Criterion:	Inhabitants	Structural engineers	Construction companies	Total:	Normalized score:
Quality	1.7	1.67	1.5	4.87	0.33
Feasibility		2.2	1.5	3.7	0.25
Minimizes nuisance	2.4	0.3		2.7	0.18
Costs		1.18	0.75	1.93	0.13
Aesthetics	1.23	0.5		1.73	0.12

5. Wall-floor connections

In this chapter, different types of wall-floor connections will be described. These connections must be applied to existing houses. Every connection is a level 2 method: tying the wall to the floor, as described by ARUP (2013). First, the connections that are currently used will be elucidated. Afterward, the proposed connections will be described. These connections are found in literature and are selected on whether they can be applied to an existing masonry house with timber floors. In Chapter 6, the alternative connections will be assessed based on the earlier mentioned criteria.

5.1. Current methods

Figure 9 and Figure 10 show the current level 2 methods. These methods are described by the Groninger Maatregelencatalogus (GMC) in 2020. The following description is based on the GMC (2020). When the joists are located parallel to the wall, the method in Figure 9 is used. Otherwise, the joists are situated perpendicular to the wall and the method in Figure 10 is used.

For cavity walls, the outer cavity leaf transfers the out-of-plane forces into the inner cavity leaf via the wall ties. The total seismic loading is transferred to the floor diaphragm via the wall-floor connection. In the case of a stability wall, the connection also transfers the shear forces, caused by seismic activity in-plane, from the floor to the wall. This connection is made from chocks, which are connected to the joist with anchors and screws. The resulting reaction forces are transferred to the wall parallel to the span direction of the floor, via the joist ends to the masonry.

In case the joists are located parallel to the wall, a gap exists between the rim joist (the joist closest to the wall) and the wall. This gap of approximately 50 mm needs to be filled up, to prevent the anchors from bending. Usually, this is done with wooden wedges. The wedges transfer the eccentricity from the anchors to the floor diaphragm. This results in a vertical force on the rim joist and its adjacent joist. In case the wedges have insufficient capacity, the gap can be filled with casting mortar. The connection between the masonry and mortar transfers the shear forces. The anchors then only must transfer the tension forces.

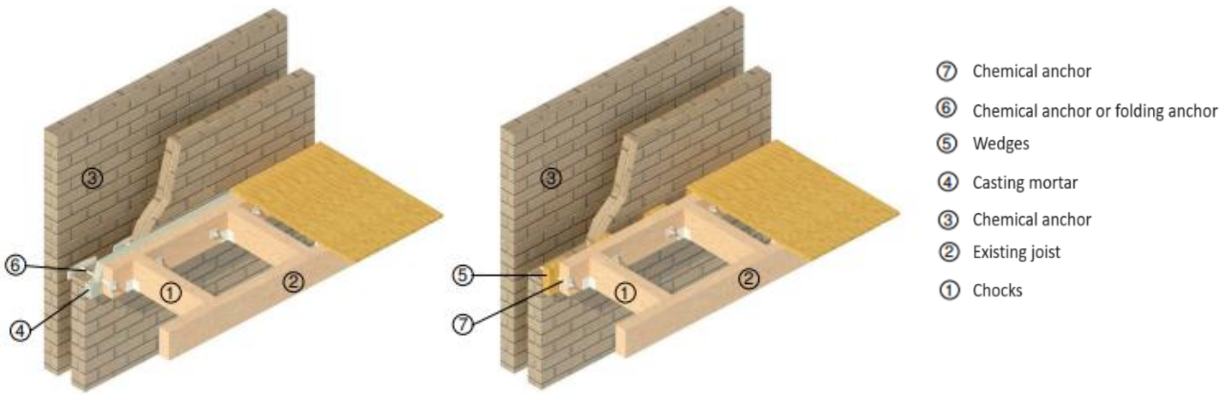


Figure 9: Level 2 strengthening measures in case of joists parallel to the wall (GMC, 2020)

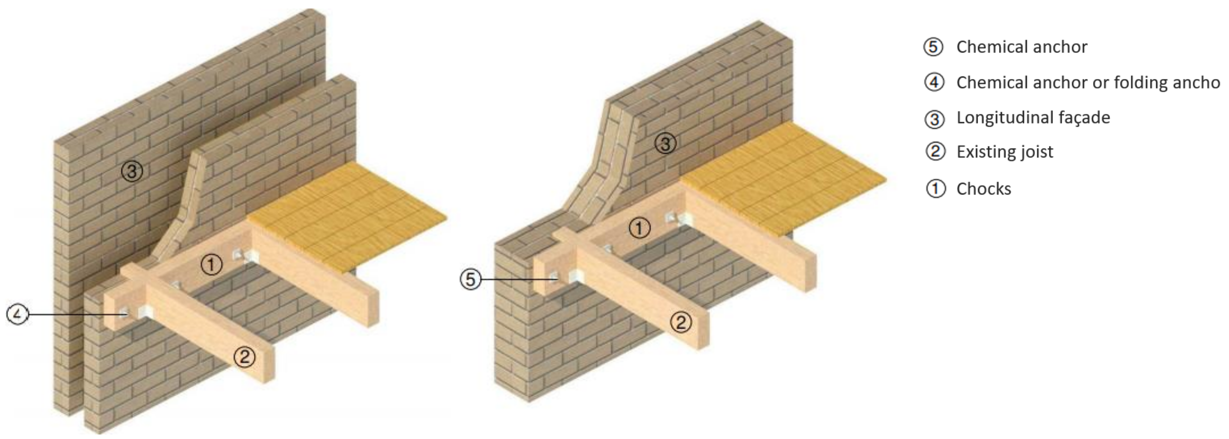


Figure 10: Level 2 strengthening measures in case of joists perpendicular to the wall (GMC, 2020)

5.2. Alternative connections

In this paragraph, the alternative connections will be described. It was aimed to find various designs, to make a good comparison. The alternatives are all found in the literature.

5.2.1. Alternative 1

The first alternative is found through the literature of the National Housing Building Code (NHBC) of the United Kingdom. According to NHBC (2021), the floor and wall can be tied with the use of a restraint strap made from galvanized steel, to take up the tensile forces. The strap is situated on top of a perpendicular joist and the center of the bricks (NHBC, 2021). An illustration of this connection can be seen in Figure 11.

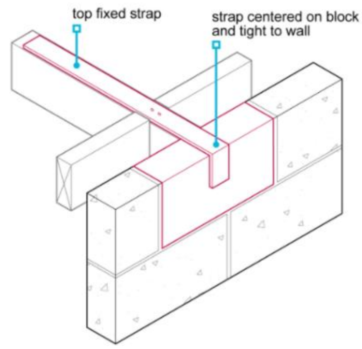


Figure 11: Restraint strap (NHBC, 2021)

The steel strap transfers tension forces via the joist, and compression forces via the connection with the brick. The performance of the design depends on the shear capacity of one brick. Especially in old buildings, it is reasonable to assume that this capacity will not be enough to withstand seismic activity. Moreover, there is a possibility that during tension, the brick will be pulled out of the wall.

This method will work well for new buildings since it is easy to apply during the construction phase. However, for existing buildings, this design is difficult to implement. The floor needs to be removed to apply the steel straps. When the floor is reapplied, it could be uneven because of the steel straps. Moreover, the steel strap needs to be applied to the middle of the brick, but the chance that the joists are connected exactly at this point is small in existing buildings.

The advantage of this design is that it does not require a lot of space. Also, when there is a cavity wall, the connection is invisible. Otherwise, the connection is visible for a little bit.

5.2.2. Alternative 2

Figure 12 shows a wall-floor connection as described by the United Nations Industrial Development Organization (UNIDO) in 1983. This method can be used when the joists are parallel to the exterior wall. The straps are anchored to the existing wall and attached to the floor in a 30-degree V-shape with multiple nails. The straps have a size of 80 x 5 mm.

According to UNIDO (1983), it is required that the wood diaphragm has enough tensile capacity beyond the straps for this design to be effective. Moreover, the strength of the connection is limited to the capacity of the masonry.

As mentioned before, the wood diaphragm needs to have sufficient tensile capacity. When this is not the case, the floor should be stiffened. Stiffening of the floor is a level 3 measure, which causes more nuisance and is more costly compared to level 2 measures. Because this research aims to find less invasive and cheaper options, stiffening the floor is undesirable.

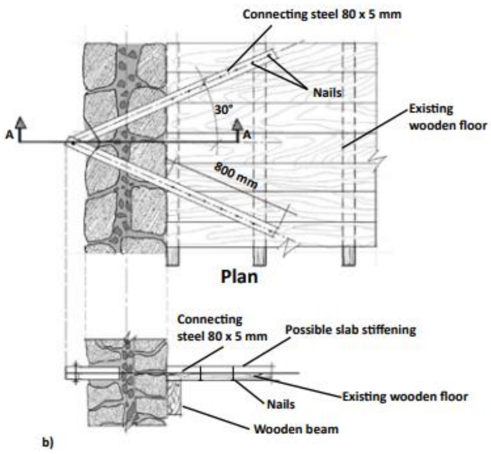


Figure 12: V-shaped steel straps (UNIDO, 1983)

When the floor does not need stiffening, the 5 mm thick steel straps can either be applied on top of the planks, which is dangerous because people can trip over them, or a top floor can be applied on the strips. An option for a top floor, that would not stiffen the diaphragm, would be laminate flooring. However, this would still cause nuisance, because all the furniture needs to be removed. When reapplying the existing floor, there is a chance that the floor would be uneven.

Another disadvantage of this method is that applying the steel strips precisely at a certain angle is tricky. Also, the steel strips stick out of the wall, which is aesthetically unpleasing. In the case of a cavity wall, the steel strips cannot be connected to each other within the cavity wall, which is inconvenient.

5.2.3. Alternative 3

The third wall-floor connector is the design by van Dijk (2015). The steel connection is L-shaped and has an anchor in the cavity wall. The anchor is T-shaped and inserted from the inside. When the anchor is situated in the cavity wall, the anchor is turned 90 degrees, so it is attached to the inside of the inner cavity leaf. It needs to be kept in place during shaking to avoid rotation, for example with epoxy. In the vertical direction, the L-shape is connected to the floor beams with nails to the joist. The wall ties are like the current level 2 connections. In Figure 13, an OSB plate is added to provide stiffening of the floor. In this research, the floor stiffening will be disregarded because this is a level 3 method, which is undesirable in the aim of this research.

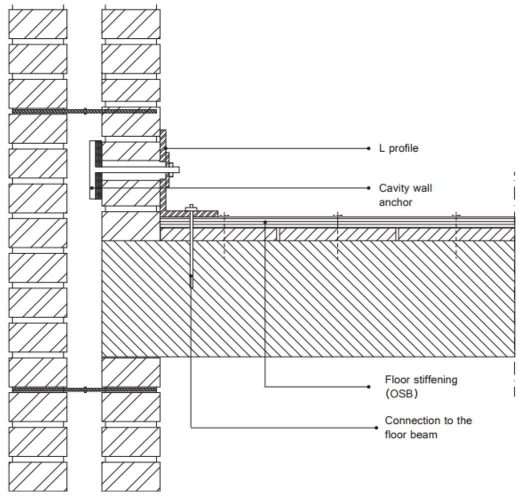


Figure 13: L-shaped steel profile (van Dijk, 2015)

The anchor transfers the forces from the wall to the floor. The connection should be applied over the whole length of the wall to prevent local failure. The anchor should be applied repeatedly with a certain distance in between.

The advantage of this design is that when the connection is finished off with carpentry, the aesthetics of this design will be goods since it is barely visible then. However, at the location where the anchors are placed, it would be more difficult to properly finish it off. The bolt would be too high to finish off with a baseboard, and the bolt buttons are big.

5.2.4. Alternative 4

In Figure 14, a connection between the wall and the floor with the use of a hook anchor can be seen. The hook is attached to one side of the joists with nails and clamps to the outer side of the wall. This is a traditional way of tying the floor and the wall which was usually applied during the construction phase. Mirra & Ravenhorst (2019) suggest that it can be used as a retrofitting technique as well.

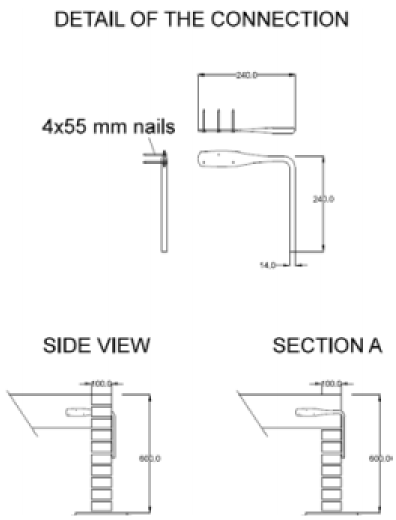


Figure 14: Connection with hook anchor (Mirra & Ravenhorst, 2019)

According to Mirra & Ravenhorst (2019), there is a chance the mortar will crack, and frictional sliding of the hook anchor and the joist, when a compression force is applied. In the tension direction, the cracking of masonry is the main possible failure mechanism (Mirra & Ravenhorst, 2019). Failure of the hook anchor itself is unlikely, due to its large diameter (Mirra & Ravenhorst, 2019). While the ductility is high in compression, the strength of the connection is very low according to Mirra & Ravenhorst (2019).

The connection can be applied when the masonry is not damaged (Mirra & Ravenhorst, 2019). Unfortunately, the chance that houses that need strengthening already have some damage is quite high.

To apply this connection, the ceiling must be removed to connect the hook anchor to the joist. This is undesirable. The length of the hook anchors on the exterior side of the wall is 240 mm. When there is a cavity wall, the anchors are not visible. However, when this is not the case, the hook anchors will be visible from the outside of buildings and thus change the appearance of the building. Since this is a traditional way of constructing a house, the change of appearance is less impactful compared to other designs, for example alternative 2 or 6.

5.2.5. Alternative 5

Figure 15, shows a connection between the joist and the wall with the use of screws at 45 degrees in the vertical and horizontal plane. This method can completely be executed from the outside of the building (Mirra & Ravenhorst, 2019). According to Mirra & Ravenhorst (2019), the holes must be drilled first. These holes will then be injected with epoxy. Next, the screws are inserted. This is a time-consuming process. Also, finding the location of the joist from the outside is difficult.

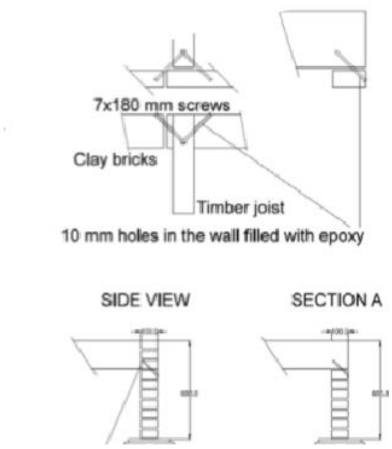


Figure 15: Screws of 45 degrees in horizontal and vertical plane (Mirra & Ravenhorst, 2019)

The quality of the design depends on the capacity of the nails and the masonry condition. According to Mirra & Ravenhorst (2019), this connection results in a significant improvement in the strength and stiffness of the building. However, the chance of local failure is high since only a small area of stone is drilled through. The main failure modes are cracks and damage to the masonry (Mirra & Ravenhorst, 2019). Since the masonry condition in Groningen is often low, the chance of this type of failure is quite high.

The main advantage of this alternative is that it is barely visible from the outside of the building. Unfortunately, the method of applying this design is time-consuming and has a high risk of failure during construction.

5.2.6. Alternative 6

The last design is called the 'Spouwdonut'. This connection was the winner of the NAM design contest in 2015. First, a steel pin is drilled from the exterior wall into the joist of the house. On top of that connector, a small sphere is inserted. This sphere will be blown up with polyurethane (PU), which causes the sphere to look like a donut, hence the name, see Figure 16. T

The tension forces are taken up by the steel connection, while the donut takes up the compression forces. This results in high quality of the connection.

According to de Leeuw (2020), this alternative has only been implemented in a few houses. The cause for this is unknown, but experts suggest that it is because the construction industry is traditional and therefore not eager to implement novel designs.

The main advantage of this design is that the construction can completely be executed from the outside of the building. However, it might be difficult to find the location of the joists from the outside of the house. Another major disadvantage is that, on the outside of the house, there is a steel plate. While this plate can be covered with a decorative ornament, it still has a large impact on the exterior façade of the houses.

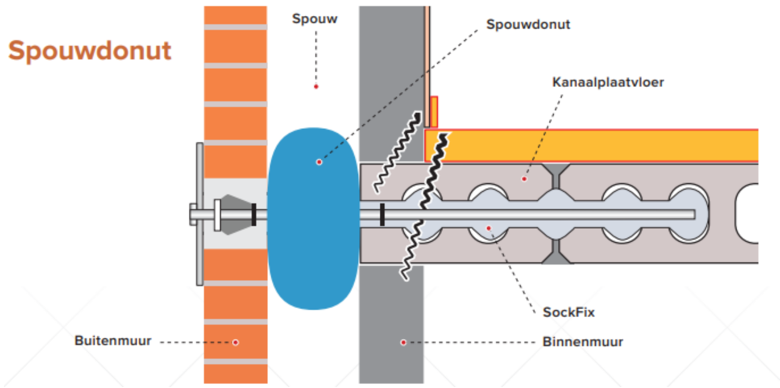


Figure 16: Schematical drawing of the Spouwdonut (TotalWall, n.d.)

6. Multi-criteria analysis

To choose the most suitable design of the alternatives as described in Chapter 5.2, the designs will be compared with the use of multi-criteria analysis. Each of the alternatives will be compared baes on the earlier drawn-up criteria. This comparison can be found in Appendix F: Comparison of criteria. This comparison resulted in a score between 1 and 11 per criterion, 1 representing the worst alternative based on a certain criterion, and 11 meaning the alternative is best based on that criterion. This score will be normalized during the analysis.

For the analysis, the Weighted Product Model (WPM) has been used. This method has been chosen because it is dimensionless Triantaphyllou & Sanchez (1997). The alternatives are compared to each other which results in a certain ratio. This ratio is then raised to the power of the criteria, as described in5.2.5 Chapter 4. The product of these outcomes then determines the performance score of each alternative. The alternative with the highest score will be the most suitable design, and therefore ranked highest. A step-by-step calculation can be found in Appendix G: Weighted Product Model.

6.1. Assessment of alternative measures

In Table 3, the outcome of the multi-criteria analysis can be seen. Alternative 3 and alternative 5 score the highest of the connections. While the aesthetics, costs, and minimizing of the nuisance of alternative 5 is better than alternative 3, alternative 3 scores higher on quality and feasibility. The quality of a connection is the most important feature, so therefore alternative 3 is the most suitable design.

Table 3: Results of the multi-criteria analysis

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics	Performance score	Rank
Weight	0.33	0.25	0.18	0.13	0.12		
Alt 1	0.47	0.55	0.83	0.94	0.95	0.19	6
Alt 2	0.89	0.72	0.83	0.84	0.81	0.37	4
Alt 3	**1**	**1**	**0.92**	**0.94**	**0.98**	**0.85**	**1**
Alt 4	0.67	0.86	0.65	0.94	0.91	0.32	5
Alt 5	0.80	0.95	0.96	1	1	0.73	2
Alt 6	1	0.86	1	0.73	0.81	0.51	3

6.2. Comparison with existing measures

When comparing alternative 3 to the existing level 2 measures, the minimization of nuisance is mainly noticeable. For the existing level 2 measures, the ceiling needs to be removed, while for alternative 3 only a small part of the floor needs to be removed and finished off. Only at the anchors, finishing off the connection is a bit more difficult because of the bolt head. The final aesthetics of the three connections are similar, although for the current level 2 measures, more work is required to properly finish the construction to the previous state. Hence, the costs and nuisance are lower for alternative 3. The feasibility of the existing connections is higher since these have been applied already. The quality of alternative 3 can only be speculated, while the quality of the existing measures can be proved.

6.3. Sensitivity analysis

To get more insight in the Weighted Product Model (WPM), a sensitivity analysis has been executed. This analysis focusses on two major elements, the criteria and the alternatives. The sensitivity analysis has been conducted with the method described by Triantaphyllou & Sanchez (1997). First, the sensitivity of the criteria has been examined. It is explored which criterion is relatively most critical. To do so, the critical degree and the sensitivity coefficient are calculated. The critical degree is the smallest percentage by which the current value of the criterion must change, in order to change the current ranking of the alternatives (Triantaphyllou & Sanchez, 1997). The sensitivity coefficient is the reciprocal of the critical degree. The criterion with the highest sensitivity coefficient is the most critical criterion.

Table 4: Outcome of sensitivity analysis per criterion

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics
Sensitivity coefficient	0.09	0.03	0.004	0.05	0.03

In Table 4, the outcome of the sensitivity analysis can be seen. The entire calculations can be found in Appendix H: Sensitivity analysis of MCA. The quality is relatively most critical, followed by the costs, feasibility, aesthetics and lastly minimizes nuisance. This means that quality has the most influence on the ranking of a certain criteria. Coincidentally, this is also the criteria with the highest weight.

Next, the sensitivity per alternative is examined. It is calculated how much the current performance score must change in order to change the ranking of two of the alternatives. To determine this, the critical degree per alternative is calculated, which is the smallest percentage by which the current performance score must change to change the ranking of the alternative. The reciprocal of the critical degree is the sensitivity coefficient.

Table 5: Sensitivity coefficient per alternative

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics
Alternative 1	0.003	0.001	0.001	0.000	0.000
Alternative 2	**0.030**	0.024	0.019	0.015	0.015
Alternative 3	0.027	0.022	0.018	0.015	0.014
Alternative 4	0.020	0.014	0.011	0.010	0.010
Alternative 5	0.017	0.013	0.012	0.011	0.011
Alternative 6	0.016	0.014	0.012	0.011	0.011

From Table 5 it can be concluded that the most critical alternative is alternative 2 since this alternative has the highest sensitivity coefficient. This means that this alternative is most likely to change in ranking when a different score for quality is assigned. The full calculations can be found in Appendix H: Sensitivity analysis of MCA.

6.4. Conclusion & Recommendation

From the multi-criteria analysis, it could be concluded that alternative 3 is the most suitable connection for existing houses in Groningen. When comparing the alternative to the current strengthening measures, the alternative scores better on minimizing nuisance and costs. The aesthetics of the alternative and the existing measures are somewhat similar. The feasibility of the currently used connections is better. The quality of the alternative is not yet tested, so it cannot properly be compared to the existing connections.

The main point of improvement of alternative 3 is to find a way around the big bolt head on the inside of the wall. Also, in case there is no cavity wall, the design will be visible from the outside of the building, which changes the aesthetics. This could be solved by adding an ornament anchor plate or by adjusting the anchor so that it would not be visible from the outside of the house. In the next chapter, a suggestion for an improvement of this design will be made.

7. A new design

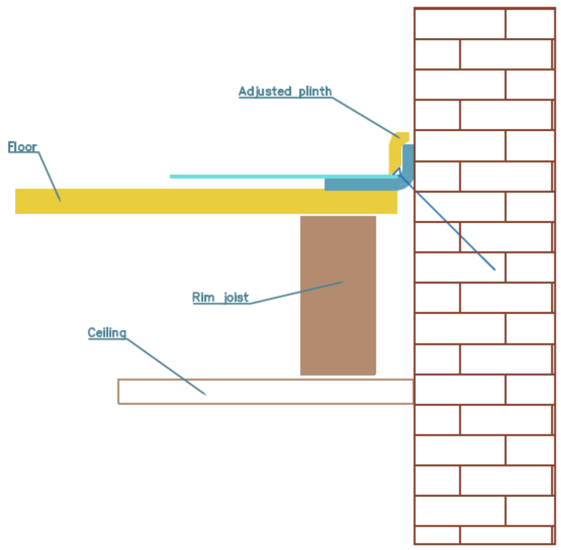


Figure 17: Connection in case of a joist parallel to the wall

As mentioned before, the most suitable design is alternative 3. However, the major disadvantage of this design is the large bolt head on the inside of the wall and that the connection is less aesthetically pleasing in case there is no cavity wall. Moreover, when there is no cavity wall, alternative 3 is not that aesthetically pleasing. One of the experts, Gerard van Engelen, designed a connection that can be seen as an improvement of alternative 3. The idea of the L-shaped connection remains, which was the major advantage of alternative 3 because the ceiling did not have to be removed. The bolt head and T-shaped anchor will be replaced with a screw in epoxy diagonally in the masonry. This way, the floor is connected to multiple bricks, which increases the technical performance of the design. Moreover, the connection can easily be finished off with a plinth.

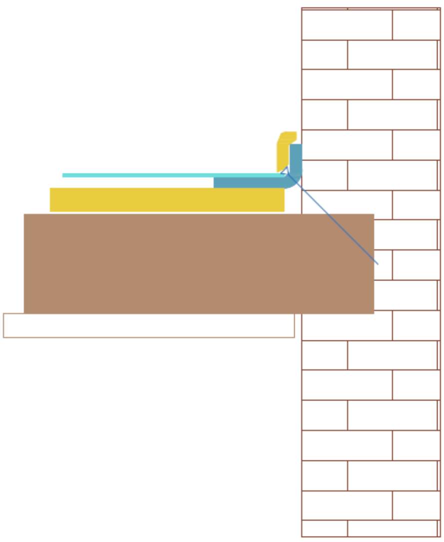
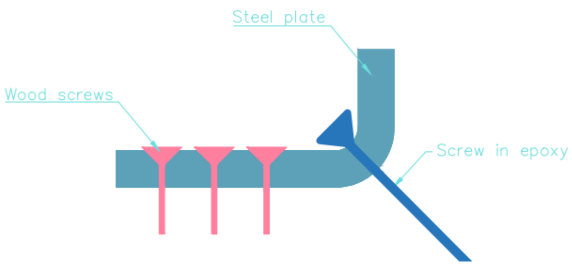


Figure 18: Connection in case of joists perpendicular to the wall

Figure 17 shows the proposed design by van Engelen (2021). As can be seen, the steel plate is thin, 1 to 1.5 mm think and 1.5 meters long. This way, the plate is practical to apply within a house. The plate is connected to the joist or planks with 3 rows of screws which are attached with staggered holes with a center-to-center distance of 50 mm. The screws are short in the planks and long in the joists. In the case of a joist perpendicular to the wall, the screw is diagonally attached to the wall and then connected to the brick as can be seen in Figure 18. Otherwise, the screw is directly attached to the bricks at a 45-degree angle. This screw is applied every 10 or 20 centimeters.

Because the steel plate is this thin, it will deform plastically when a force is applied. The steel around the horizontal screw will yield. The anchors and screws are laterally loaded by the horizontal force caused by the acceleration during an earthquake.



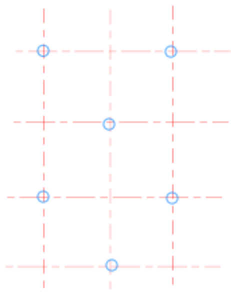


Figure 19: Detail of the connection

8. Discussion

From the multi-criteria analysis, it is found that alternative 3 as designed by van Dijk is the most suitable connection for the situation in Groningen. This conclusion is based on the criteria put together from the stakeholder interviews. However, in total, only 4 inhabitants, 2 construction companies, and 5 structural engineers have been interviewed. This is far from significant from the 600 000 people affected by this problem (Vlek, 2018). Moreover, having a low response rate increases the chance of people misunderstanding the questions. Because the interviews were held via telephone, people might not have the chance to think deeply about their answers. Regarding the interviews with the structural engineers, the results might be better to have a brainstorming session with multiple experts to come to an understanding of the most suitable alternative together. This way, the designs could be discussed, and pros and cons could be reviewed.

The interviews with structural engineers intended to hold a semi-structured interview with the questions found in Appendix D: Interview questions for structural engineers. In reality, a dialogue started during the interviews, which obstructed me from asking each of the questions. The questions were used more as a guideline of topics to discuss, without asking each of them in a certain order. The time set out for the interviews was one hour. For some experts, the interview lasted around 40 minutes, while with others I spent 90 minutes. This resulted in certain topics being more extensively discussed in one interview and being less discussed in the other. On one hand, this was a good thing. It allowed the experts to talk about the topics they valued important and had the most knowledge about. On the other end, it resulted in distorted answers for the intended questions. This can be seen in Appendix E: Results interviews with structural engineers

In the selection of the criteria, it is assumed that the criteria of every stakeholder are of equal importance. However, one could argue that the criteria from the inhabitants are more important compared to the criteria from the structural engineers because the inhabitants are directly affected. On the other hand, the structural engineers might consider the criteria that inhabitants might find important, such as nuisance, while the inhabitants did not consider the practicality in their criteria. Moreover, not every stakeholder has been interviewed. The stakeholders that were not interviewed might value other criteria, or might prioritize the criteria differently, which would result in a different solution.

In the report, it is noticeable that almost everyone involved would benefit from a quick solution. In the multi-criteria analysis, quickness is implied in the criteria ‘Minimizes nuisance’. If this is such an important criterion, it could be considered to use a separate criterion for the assessment of the time required to implement a connection.

During the multi-criteria analysis, these criteria were used to compare the alternative connections. One of the criteria was quality. When comparing the alternative connections, the quality was, in most cases, estimated with the help of the experts. However, when the most suitable connection was compared to the current design, it was mentioned that the quality could not be compared because the alternative test was not yet tested. The reasoning behind this is that the quality of the current measures is good, but one can only speculate about the quality of the alternative. When comparing the alternatives in the multi-criteria, everything is based on speculations. However, when comparing the alternative connection to the existing connection, one must compare a proven quality with a speculated quality. Therefore, a proper comparison is difficult to make in this time frame.

The most suitable connection according to the multi-criteria analysis is alternative 3. However, this design scores differently when a house does not have a cavity wall since the connection is then visible from the outside of the building. This has not been considered in the analysis.

9. Conclusion

9.1. Conclusion

In this report, research has been done to find an improved wall-floor connection to strengthen existing houses in the Groningen region. This research was executed because the current way of strengthening causes nuisance for the inhabitants, is expensive and time-consuming. The report aims to answer the following research question: Which recommendations can be made after comparing the quality of different alternative designs for the wall-floor connections in the Groningen region?

To answer this question, literature research was performed firstly. This research provided information for the technical framework as described in Chapter 3. Next, a stakeholder analysis was performed to give insight into the objectives of the parties involved. Additionally, several stakeholders were interviewed regarding their demands for a novel strengthening method. With this information, criteria were composed. The weight of each of the criteria was also provided by the stakeholders. These criteria formed the basis for the multi-criteria analysis in which several alternative wall-floor connections were compared.

The multi-criteria provided the choice for the most suitable alternative, which is the L-shape connection as described by van Dijk (2015). This connection is applied from the upper side of the floor and is secured with a T-shaped anchor in the cavity between the inner and outer leaf of the cavity wall. This way, the appliance of the connection is less extensive, and it can be easily finished off with carpentry. The main disadvantage of the design is that at the location where anchors are situated, the bolt head is difficult to properly finish off since it probably cannot be touched up with a plinth.

To enhance this connection, an improved design is made by van Engelen (2021). This design is also L-shaped, but instead of the T-shaped anchor, a screw is diagonally inserted in the masonry. This way, the connection depends on the shear capacity of multiple bricks. The horizontal side of the steel plate is connected to the joist or planks with screws.

9.2. Recommendation

As mentioned before, this research aims to recommend how to proceed with strengthening houses. Since the designs by van Dijk and van Engelen are both promising, it is recommended to research the technical performance of these connections. This way, a proper comparison can be made with the current strengthening measures. A way to finish off the bolt head in the design by van Dijk should also be examined to see whether this might be possible.

Additionally, it should be examined whether the design meets the design requirements as described by the NPR 9998. It should meet these requirements to be legally implemented.

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Appendix

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Appendix A: Stakeholder table

Table 6: Overview of the stakeholders

Stakeholder	Interest/ task	Desired situation/objective	Existing or expected situation and gap	Causes	Possible solutions
Inhabitants of the earthquake region	To live safely and not have damage and/or decreasing values of their houses.	Getting their houses reinforced quickly decreases the chance of damage and value decrease, without having nuisance from it.	It takes a long time until the houses get strengthened and when it happens it causes a lot of nuisance. Moreover, the value of their houses is decreasing due to earthquake damage.	Currently, it takes a long time until the houses get reinforced, and when it happens it causes nuisance.	A strengthening measure that causes less nuisance, for example, because the inhabitants do not have to move out of their house.
Arcadis/ consultancy firms	Arcadis is one of the consultancy firms hired by Nationaal Coördinator Groningen to strengthen buildings in Groningen. Their interest is to get as many projects as possible.	To offer adequate solutions to their customer, NCG.	The time between the assessment of houses and the planning of reinforcement takes on average 1.6 years (SodM, 2020).	The current way strengthening measures are expensive and complex.	A general solution for a group of similar houses that could be implemented quickly without extensive calculations.
Nationaal Coördinator Groningen (NCG)	The NCG is responsible for the strengthening decision and the execution. This means that the NCG is the client for engineering consultancies such as Arcadis. NCG describes its interest as: reinforcing houses and buildings in the earthquake area for the inhabitants.	Getting all the houses that need reinforcement, reinforced as quickly as possible.	It takes a long time until the houses get reinforced. On average, the houses that went through the complete process took 3.4 years to complete (SodM, 2020), and the longer it will take, the higher the chance of (more) damage.	Currently, it takes a long time until the houses get reinforced because the current strengthening method is time-consuming.	A quicker design of strengthening.
Construction companies	Construction companies must execute the plans made by the consultancy firm. Their interest is to execute the construction properly.	Properly strengthening the houses without it being costly or too invasive.	An expected situation could be that the consultancy firms design a measure that is innovative, but barely executable, which would make the construction difficult.	The consultancy firm designs a solution that is innovative but barely executable.	A more practical and cost-effective solution for strengthening the houses could be applied to a group of similar houses.

Municipalities in the earthquake region	Make the plan of approach (PvA) for the strengthening of houses in their municipality. They want to have the houses strengthened as soon as possible because the situation causes a lot of inhabitants to move away from the area (Ministerie van Economische Zaken en Klimaat, 2019).	The municipality wants to guarantee safety for its inhabitants, preferably as soon as possible (het Hogeland, 2020).	More people moving away, and municipalities do not attract new inhabitants (Mulder & Perey, 2018)	The strengthening of houses takes a long time.	A quicker way to strengthen the houses.
Ministerie van Economische Zaken en Klimaat	The responsible party for safety in the earthquake region. The minister checks the safety with independent parties and committees (Ministerie van Economische Zaken en Klimaat, 2019).	That all the houses meet the safety norms cost-effectively.	Not all houses are safe yet and proposed solutions can be expensive.	For only 30% of the houses of the work stock of NCG, it has been reviewed if the houses meet the safety norm (NCG, 2021). Of the work stock, only 7% has been finalized (NCG, 2021). This means a lot of houses do still not meet the safety norm.	A quicker way of strengthening the houses.
Staatstoezicht op de Mijnen (sodM)	Monitors the strengthening of houses, and judges whether the plan of approach is targeted on quick strengthening and if it meets the standards (Ministerie van Economische Zaken en Klimaat, 2019). Is interested in the safety and protection of the environment.	Safe and sustainable houses for everyone.	Not all houses are safe yet.	For only 30% of the houses of the work stock of NCG, it has been reviewed if the houses meet the safety norm (NCG, 2021). Of the work stock, only 7% has been finalized (NCG, 2021). This means a lot of houses do still not meet the safety norm.	A quicker way of strengthening the houses, which is sustainable for the future situation.
Nationale Aardolie Maatschappij (NAM)	The NAM is the financing party of the strengthening measures. As of 2020, NAM does not influence the decisions and execution of the strengthening measures.	A cheap way of strengthening the houses.	Currently, NAM thinks that they must pay too much money for the strengthening of houses in the region, among other things because of strengthening measures that are too extensive than necessary (NOS, 2021).	The NAM thinks that the norms for strengthening measures are too strict (Braakman & Miskovic, 2021).	Less extensive strengthening measures to reduce the costs.

Appendix B: Inhabitant interviews

Appendix B.1: Answer sheet B. Jacobs

Name: Ben Jacobs
Date: 2021, May 25
Place of residence: Uithuizermeeden
Homeowner/rental: Rental

Which criteria do you think are important?

The houses need to look the same, otherwise, the village would not look the same. Also, it must be done as quickly as possible. Rather yesterday than tomorrow. But the rules of the NCG keep changing so we do not know when it will happen.

Prioritize the criteria.
Which property would win?

Table B1: Outcome interview B. Jacobs

	House needs to look the same	**Quick**	**Total:**	**Score:**
House needs to look the same		0	0	0
Quick	1		1	1

Appendix B.2: Answer sheet R. Hekma

Name: R. Hekma
Date: 2021, May 25
Place of residence: Leermens
Homeowner/rental: Owner

Which criteria do you think are important?
The quality of course, and I do not want to lose space in my house. Moving out of my house would also not be acceptable. Of course, my house must look the same afterward.

Prioritize the criteria.
Which property would win?

Table B2: Outcome interview R. Hekma

	Quality	Loss of space	Moving out of building	Same look of building	Total:	Score:
Quality		0	0	0	0	0
Loss of space	1		0	1	2	0.66
Moving out of building	1	1		1	3	1
Same look of building	1	0	0		1	0.33

Appendix B.3: Answer sheet K. Hasperhoven

Name: K. Hasperhoven
Date: 2021, May 26
Place of residence: Winsum
Homeowner/rental: Owner

Which criteria do you think are important?
We have had adjustments to our house due to damage in the masonry, that lasted 2 weeks. I would have appreciated it if it would be done more quickly. Afterward, the damage was back relatively soon, so, in contrast to our adjustments, the solution should be durable. It must be a good-looking solution, but I would not mind if you saw it a little bit. The worth of the house should not decrease. The worth of the house decreases when the adjustment does not suit the house, or if the quality of the appliance of the measure is bad. So, the quality of the appliance and the quality of the measurement is important as well. NB: it must be mentioned that in this conversation, the criteria aesthetics and quality, as well as durable and quality are used somewhat interchangeably.

Prioritize the criteria.
Which property would win?

Table B3: Outcome interview K. Hasperhoven

	Quick	Aesthetics	Durable	Quality	Total:	Score:
Quick		0	0	0	0	0
Aesthetics	1		0	0	1	0.33
Durable	1	1		0	2	0.66
Quality	1	1	1		3	1

Appendix B.4: Answer sheet M. van den Bergh

Name: van den Bergh
Place of residence: Groningen
Date: 2021, June 3
Homeowner/rental: Homeowner

Which criteria do you think are important?
Safety. Also, I want to have my own control over what is going to happen and when. It must be good-looking, but it does not have to look exactly the same. Less nuisance as possible, and of course it should be durable.

Prioritize the criteria.
Which property would win?

Table B4: Outcome interview M. van den Bergh

	Safety	Own control	Good-looking	Least nuisance	Durable	**Total**	**Score**
Safety		1	1	1	1	4	1
Own contol	0		1	1	1	3	0.75
Good-looking	0	0		1	0	1	0.25
Least nuisance	0	0	0		0	0	0
Durable	0	0	1	1		2	0.5

Appendix B.5: Final criteria of inhabitants

In this chapter, the final criteria with their absolute score, as well as their average score per person are displayed. Every time a criterion was mentioned by one of the stakeholders, it received one point. On top of that point came the points from the prioritization, between 0 and 1. The results from the scoring system can be seen in Table B5.

Table B5: Criterion mentioned by inhabitants.

Criterion:	**Score:**	**Per person:**
Quality	6.7	1.7
Aesthetics	4.91	1.23
Minimizes nuisance	9.41	2.4

Appendix C: Construction company interviews

Appendix C.1: Answer sheet Bouwbedrijf Appingedam

Name: Geert Jan Huiges
Date: 2021, June 2
Company: Bouwbedrijf Appingedam

Do you experience a problem with the current way, if so, what is this problem?
It is bothersome to remove the ceiling, but you will always keep that problem. I do not see another way. If you would have to remove the floor, you will have to move all the furniture and reapply the floor, I do not see why that is better.

Which criteria do you think are important for a future design of a strengthening measure?
Eventually, everything comes down to time and costs. Time = money, because time and money both depend on the level of difficulty, whether the people need to leave their house, etc.

Rate the criteria.
Which criterion would win?
According to the expert, the criteria are co-dependent so they cannot be prioritized.

Criteria	Score
Time	0.5
Costs	0.5

Appendix C.2: Answer sheet BAM

Name: Kees Versluijs
Date: 2021, June 2
Company: BAM

Do you experience a problem with the current way, if so, what is this problem?
A few years ago, I worked on a similar problem like this. I designed some of the current strengthening measures. At that time, I was involved in this problem, but nowadays I think it works well. Of course, there is always room for improvement.

Which criteria do you think are important for a future design of a strengthening measure?

- Transferring the forces
- Quickly executable to cause lower costs.
- Reliability → multiple tests should be executed to ensure the reliability of a design in multiple circumstances.

Rate the qualities.
Which property would win?

Table C1: Outcome interview BAM

	Transferring forces	**Quickly executable**	**Reliability**	**Total:**	**Score:**
Transferring forces		0	0	0	0
Quickly executable	1		0	1	0.5
Reliability	1	1		2	1

Appendix C.3: Final criteria construction companies

In this chapter, the final criteria with their absolute score, as well as their average score per person are displayed. Every time a criterion was mentioned by one of the stakeholders, it received one point. On top of that point came the points from the prioritization, between 0 and 1. The results from the scoring system can be seen in Table C2.

Table C2: Criteria mentioned by construction companies.

Criterion:	**Score:**	**Per person:**
Costs	1.5	0.75
Quality	3	1.5
Feasibility	3	1.5

Appendix D: Interview questions for structural engineers.

The following questions will be asked during the interview.

1. **Problem perception**

1.1. What is the problem with the current way of strengthening the wall-floor connections in your perspective?
1.2. Which parties are affected by this problem?
1.3. What is the role of Arcadis in this problem?

2. **Criteria**

2.1. Which factors are important to evaluate solutions (e.g. costs, aesthetic, executability)
2.2. On a scale of 1 to 5, how important would you rate each of these criteria?

3. **Proposed solutions**

Explain each of the proposed solutions from the literature. Ask the following questions per solution.
4.1. What is your first impression of solution x? why?
4.2. How do you think this solution will behave during an earthquake (technical performance)?
4.3. What do you think the inhabitants will think of this solution?
4.4. Do you think the solution is better than the current way? Why (not)?

4. **Remaining questions**

This question aims at finding whether the expert wants to revise or add something to its previous answer to question 1 to 3. It is also a way to check whether the interviewer has a clear understanding of the answers of the expert. The interviewer starts with: your answer to question x was …, do you want to revise or add something to your answer? This is done because approving or rejecting the proposed solutions might give the expert more insight into the problem, design requirements, and/or criteria. At last, the interviewer will ask the expert whether there is any remaining information that he would want to add to this interview.

Appendix E: Results interviews with structural engineers

Appendix E.1: Answer sheet Arvin van Heest

Name: Arvin van Heest
Date: 2021, May 4
Function: structural engineer

1. **Problem perception**

The problem consists out of 2 factors. First, the current way of strengthening costs money, which the NCG does not have. Secondly, the inhabitants are not happy because the strengthening measures have a big impact on their house.

2. **Criteria**

The criteria that are important to evaluate the solutions are:

1. Quality → Does the design hold during an earthquake?
    a. Importance = 10/10
2. Executability → And thus the costs. If the solution is very expensive, the NCG does not want to pay and the solution will not be executed
    a. Importance = 7.5/10
3. Aesthetics
    a. Importance = 8/10

3. **Alternatives**

Table E1: Answer sheet Arvin van Heest

Designs	**Quality**	**Nuisance**	**Feasibility**	**Aesthetics**	**Costs**
Alternative 1	Doubts about the quality of the connection. The strength of the mortar is unknown.	You should have to take out the floor to apply this connection.		Aesthetically this solution is good, barely can be seen from the outside.	

Alternative 2	Strong connection. Less chance of local failure compared to the first solution.		You must go through the wall at a certain angle, that is tricky.	Aesthetically it is fine, but you will see it from the outside.	
Alternative 3	The connection should be all over the wall, otherwise, there is a chance of local failure. Anchors once per 1 or 2 meters probably. Quality is good			One of the most beautiful solutions, nothing to see from the outside.	
Alternative 4	Quality is good. Take into account: that the wall cannot displace as much as the floor.	Since the construction can completely be executed from the outside, it is inhabitant friendly.	Especially suitable for a half brick wall and a full brick wall.		
Alternative 5	Better connection than 4, because it supports both the in-and-out of plane direction, as well as the left and right direction.		Especially suitable for a half brick and a full brick wall.		
Alternative 6	Good quality, there is a reason this design was a price winner.		The reason why it was never implemented was that the construction industry is traditional.	Aesthetically good, you only see a small plate from the outside.	

4. Remarks

Appendix E.2: Answer sheet Piet van Bezu

Name: Piet van Bezu
Date: 2021, May 4
Function: Senior structural engineer

5. **Problem perception**

The main problem is that the strengthening measures cost money that the NCG does not have. So now Arcadis proposes solutions that NCG does not want to pay.

6. **Criteria**

The important criteria are, with descending importance:

1. Taking up the forces, quality
2. Costs
3. No negative impact on the functionality of the building
4. Easily executable, quick
5. Aesthetic

NB: when working on cultural heritage buildings, aesthetics is most important.

7. **Alternatives**

Table E2: Answer sheet Piet van Bezu

Designs	**Quality**	**Nuisance**	**Feasibility**	**Aesthetics**	**Costs**
Alternative 1	The quality depends on the capacity of the stone it is attached to. This would most certainly not work for existing houses in Groningen	-	-	-	-
Alternative 2	Would probably work	You need to add a floor because otherwise			

		there is the danger of tripping. This will create a lot of nuisance because the house needs to be adjusted: doors need to be shortened, what to do with the staircase?			
Alternative 3	Would work during an earthquake. Stiffening the floor is not necessary.			Needs to be finished with carpentry, then it is fine.	
Alternative 4	Would work in theory, but not implementable		Inserting the anchor from the outside is practically not feasible.	Aesthetically not good, because you must find the joist from the outside. This will cause damage which then needs to be repaired	
Alternative 5	Would probably work, but it would depend on the capacity of the screws			Aesthetically fine.	Costs would be fine.
Alternative 6	Quality is good, but there is a reason why this was never implemented.		Pumping up the sphere needs to be done controlled. It needs to be pumped up big enough to take up the forces, but not too big because then the exterior cavity wall will displace.		

8. Remarks

After war floors are often very fragile, for example, pefora floors. You should also consider this!

Appendix E.3: Answer sheet Gerard van Engelen

Name: Gerard van Engelen
Date: 2021, May 10
Function: Senior structural engineer

9. **Problem perception**

Currently, the ceiling needs to be taken out of the building. Also, the quality of the masonry is not that good, especially on top of the wall (beneath the roof). The strengthening measures are limited to the shear capacity of the masonry. Another big problem is finishing off the measures.

10. **Criteria**

The following criteria are important:

1. Relatively simple solution
2. Easy to apply.
3. Little elements to take away.
4. Costs (this is implied in the other criteria)
5. Capacity

11. **Alternatives**

Table E3: Answer sheet Gerard van Engelen

Designs	Quality	Nuisance	Feasibility	Aesthetics	Costs
Alternative 1	Capacity is limited to the shear capacity of the stone	Bump in the floor		At a half brick wall, you will see it from the outside.	
Alternative 2	There is a chance the stones are ripped out of the wall	Uneven floor		You will see it from the outside	
Alternative 3	Mechanically this solution is very certain. The anchor cannot go out of the cavity wall. The anchor should be	You must make a lot of holes in the wall.		Problem with finishing off the connection since the bolt heads are rather big and high	

	once every other meter.			on the wall. Too high for a plinth.	
Alternative 4	In principle, this is how a wall should be connected, on every other joist.	The ceiling needs to be taken out because you do not want to apply this solution from the outside.			
Alternative 5	You only take a little area of stone, which gives a big chance of breaking off during the application. Also, it cannot withstand many forces.				
Alternative 6	Constructively this is a good solution.	You should watch out for a cooling leak to the outside of the house because of the metal elements.		The aesthetics are the weak spot of this connection.	

12. Remarks

Appendix E.4: Answer sheet Laverne Kruger

Name: Laverne Kruger
Date: 2021, May 10
Function: structural engineer

1. **Problem perception**

In principle, the current way of working works very well. The main disadvantage is that the whole ceiling must be removed.

2. **Criteria**

The importance of the criteria depends on your point of view. For an engineer, capacity is most important. The practicality is most important for the contractor since he needs to be able to build the strengthening measure. For the project manager, the costs are most important.

3. **Alternatives**

Table E4: Answer sheet Laverne Kruger

Designs	Quality	Nuisance	Feasibility	Aesthetics	Costs
Alternative 1			Good for a new building, but difficult for new buildings. Beams should contain to the middle of the brick		
Alternative 2	Strength depends on how many you have, but you do not want a lot of them. Stiff floor diaphragm required.		Like the first one, nice for new buildings, difficult for existing buildings.		
Alternative 3	Good connection		Construction-wise, drilling the hole might be tricky. How to keep the anchor in place during shaking? Epoxy?	L-profile and bolt heads need to be covered with plinth.	

Alternative 4	Doable in tension, because 4 lines of bricks, but what will it do in compression? Does not have a lot of compression. Will cause additional deflection. Wouldn't recommend				
Alternative 5	Good strength detail. Reliance on the masonry condition is good.	Easy to install, can be time-consuming.			Quite affordable
Alternative 6	Good detail from an engineering point of view		Needs waterproofing and compensate isolation.	Changes the look on the outside, not allowed for a monument.	Doubts on the accessibility and affordability of the connection

4. Remarks

Appendix E.5: Answer sheet Etienne van der Westhuizen

Name: Etienne van der Westhuizen
Date: 2021, May 12
Function: structural engineer

13. Problem perception

Houses in Groningen have severe deterioration of masonry work. The time is also difficult to guarantee.
Also, a lot of houses are monuments. Regarding the aesthetics: either it does not look good, or it takes a lot of work and thus money.
Trying to connect 2 old elements is a challenge.
The usability of the house often changes, because of space reduction due to the strengthening measures.

14. Criteria

As every engineering job, the main criteria are, with each of equal importance:

1. Safety
2. Durability
3. Economical/ cost-friendly

15. Alternatives

Table E5: Answer sheet Etienne van der Westhuizen

Designs	Quality	Nuisance	Feasibility	Aesthetics	Costs
Alternative 1	Not effective.	Not that invasive.			Economical
Alternative 2	When not using a top floor, you only connect 3 planks.	Invasive measure	Difficult to create this connection.	Quite visible, so owners would probably not like it.	Cheap option.
Alternative 3	The quality is good, could be increased by combining it with alternative 4.			You do not see the anchors in the cavity wall, that is positive.	Quite cheap.
Alternative 4	For a short spanning floor, this would be fine. The hook should				Cheapest option.

	be on both sides of the floor. If the hook is only present at one side, it cannot perform anymore. Clamping both sides of the wall would be better.				
Alternative 5	Same strength category as alternative 4.				Cheap solution.
Alternative 6	Would work			Aesthetically it could improve by sticking the donut chemically to the wall	Really expensive solution

16. Remarks

Also, consider a chemical solution. However, this could be messy and bad for the environment.
Each of the houses is very different, so finding a solution that works for all houses is very difficult.

Appendix E.6: Final criteria by structural engineers

In this chapter, the final criteria with their absolute score, as well as their average score per person are displayed. Every time a criterion was mentioned by one of the stakeholders, it received one point. On top of that point came the points from the prioritization, between 0 and 1. The results from the scoring system can be seen in Table E6.

Table E6: Criteria mentioned by structural engineers.

Criterion	**Score**	**Per person:**
Quality	8.33	1.67
Costs	5.88	1.18
Minimizes nuisance	1.5	0.3
Aesthetics	2.5	0.5
Feasibility	11	2.2

Appendix F: Comparison of criteria

Table F1: Comparison of the quality

Quality							**Total:**	**Score:**
	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6		
Alt 1		-	-	-	-	-	- 5	1
Alt 2	+		-	+	+	-	+ 1	7
Alt 3	+	+		+	+	+/-	+ 4	10
Alt 4	+	-	-		-	-	- 3	3
Alt 5	+	-	-	+		-	- 1	5
Alt 6	+	+	+/-	+	+		+ 4	10

Table F2: Comparison of the costs

Costs							**Total:**	**Score:**
	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6		
Alt 1		+	+/-	+/-	-	+	+ 1	7
Alt 2	-		-	-	-	+	- 3	3
Alt 3	+/-	+		+/-	-	+	+ 1	7
Alt 4	+/-	+	+/-		-	+	+ 1	7
Alt 5	+	+	+	+		+	+ 5	11
Alt 6	-	-	-	-	-		- 5	1

Table F3: Comparison of minimizing the nuisance

Minimizes Nuisance							**Total:**	**Score:**
	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6		
Alt 1		+/-	-	+	-	-	- 2	4
Alt 2	+/-		-	+	-	-	- 2	4
Alt 3	+	+		+	-	-	+ 1	7
Alt 4	-	-	-		-	-	- 5	1
Alt 5	+	+	+	+		-	+ 3	9
Alt 6	+	+	+	+	+		+ 5	11

Table F4: Comparison of the aesthetics

Aesthetics							**Total:**	**Score:**
	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6		
Alt 1		+	-	+	-	+	+ 1	7
Alt 2	-		-	-	-	+/-	- 4	2
Alt 3	+	+		+	-	+	+ 3	9
Alt 4	-	+	-		-	+	- 1	5
Alt 5	+	+	+	+		+	+ 5	11
Alt 6	-	+/-	-	-	-		- 4	2

Table F5: Comparison of the feasibility

Feasibility							**Total:**	**Score:**
	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6		
Alt 1		-	-	-	-	-	- 5	1
Alt 2	+		-	-	-	-	- 3	3
Alt 3	+	+		+	+	+	+ 5	11
Alt 4	+	+	-		-	+/-	0	6
Alt 5	+	+	-	+		+	+ 3	9
Alt 6	+	-	-	+/-	+		0	6

Appendix G: Weighted Product Model

In this chapter, a step-by-step calculation of the Weighted Product Model (WPM) will be executed. First, the weight of the criteria is determined by calculating the ratio of the weight that the stakeholders gave to the criteria.

Table G1: Final score per criterion

	Quality	**Feasibility**	**Minimizes Nuisance**	**Costs**	**Aesthetics**
Weight given by stakeholders:	4.87	3.7	2.7	1.93	1.73
Ratio	4.87/14.93	3.7/14.93	2.7/14.93	1.93/14.93	1.73/14.93
Final score:	0.33	0.25	0.18	0.13	0.12

Next, the scores given to the criteria in Appendix F: Comparison of criteria will be normalized based on the maximum value of the criterion.

Table G2: Score of each of the alternatives on the criteria

	Quality	**Feasibility**	**Minimizes Nuisance**	**Costs**	**Aesthetics**
Weight	0.33	0.25	0.18	0.13	0.12
Alt 1	1	1	4	7	7
Alt 2	7	3	4	3	2
Alt 3	**10**	**11**	7	7	9
Alt 4	3	6	1	7	5
Alt 5	5	9	9	**11**	**11**
Alt 6	**10**	6	**11**	1	2

Table G3: Normalized scores

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics
Weight	0.33	0.25	0.18	0.13	0.12
Alt 1	1/10	1/11	4/11	7/11	7/11
Alt 2	7/10	3/11	4/11	3/11	2/11
Alt 3	10/10	11/11	7/11	7/11	9/11
Alt 4	3/10	6/11	1/11	7/11	5/11
Alt 5	5/10	9/11	9/11	11/11	11/11
Alt 6	10/10	6/11	11/11	1/11	2/11

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics
Weight	0.33	0.25	0.18	0.13	0.12
Alt 1	0.1	0.09	0.36	0.64	0.64
Alt 2	0.7	0.27	0.36	0.27	0.18
Alt 3	1	1	0.64	0.64	0.82
Alt 4	0.3	0.55	0.09	0.64	0.45
Alt 5	0.5	0.82	0.82	1	1
Alt 6	1	0.55	1	0.09	0.18

Next, the scores off the alternatives will be raised by the power of the criteria. For example, alternative 1 with respect to the criterion Quality, will be 0.1^0.33 = 0.47. The scores per alternative will be multiplied, which gives the total performance score per alternative. The alternative with the highest performance score will be the most suitable design.

Table G4: Performance scores and ranks of the WPM

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics	Performance score	Rank
Weight	0.33	0.25	0.18	0.13	0.12		
Alt 1	0.47	0.55	0.83	0.94	0.95	0.19	6
Alt 2	0.89	0.72	0.83	0.84	0.81	0.37	4
Alt 3	**1**	**1**	**0.92**	**0.94**	**0.98**	**0.85**	**1**
Alt 4	0.67	0.86	0.65	0.94	0.91	0.32	5
Alt 5	0.80	0.95	0.96	1	1	0.73	2
Alt 6	1	0.86	1	0.73	0.81	0.51	3

Appendix H: Sensitivity analysis of MCA

In this chapter, the sensitivity analysis performed will be elucidated. The method followed is the Weighted Product Model by Triantaphyllou & Sánchez (1997). First, a sensitivity analysis will be performed along the criteria, to find the most critical criterion. Next, the alternatives are analyzed to find the most critical alternative.

Appendix H.1: Sensitivity analysis of criteria

The most critical criterion can be described as the absolute critical criterion and the relative critical criterion. The aim of the sensitivity analysis is to find the relatively most critical criterion. For this, the changes in the current weight are examined. The relative change is expressed with:

$$\delta'_{k,i,j} = \delta_{k,i,j} \times \frac{100}{W_k}$$, for any 1 ≤ i < j ≤ M and 1 ≤ k ≤ N [1]

With:

$\delta_{k,i,j}$ = minimum change in the current weight W_k of criterion C_k such that the ranking of alternatives A_I and A_j will be reversed.
W_k = weight of the criterion C_k

The critical $\delta'_{k,i,j}$ by which the weight needs to be adjusted to reverse the ranking of alternative A_i and A_j is as follows:

$\delta'_{k,i,j} > K$, if K ≥ 0, or:
$\delta'_{k,i,j} < K$, otherwise.

With K is:

$$K = \frac{\log\left(\prod_{y=1}^{N}\left(\frac{a_{iy}}{a_{jy}}\right)^{W_y}\right)}{\log\left(\frac{a_{ik}}{a_{jk}}\right)} \times \frac{100}{W_k}$$ [2]

Also, the following constraint should be satisfied:

$$\delta'_{k,i,j} \leq 100$$ [3]

As a reminder, the current weight with performance scores will be repeated.

Table H1: Performance scores and ranks of the WPM

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics	Performance score	Rank
Weight	0.33	0.25	0.18	0.13	0.12		
Alt 1	0.47	0.55	0.83	0.94	0.95	0.19	6
Alt 2	0.89	0.72	0.83	0.84	0.81	0.37	4
Alt 3	**1**	**1**	**0.92**	**0.94**	**0.98**	**0.85**	**1**
Alt 4	0.67	0.86	0.65	0.94	0.91	0.32	5
Alt 5	0.80	0.95	0.96	1	1	0.73	2
Alt 6	1	0.86	1	0.73	0.81	0.51	3

With this information, the possible K values could be calculated for any pair of alternatives. These can be found in Table F2. When a K value is Non-Feasible (N/F), it means that the K value was not within the boundary conditions as described in equation 3. For each criterion, the lowest absolute K value represent the critical degree. The reciprocal of this degree is the sensitivity coefficient. These values can be found in Table F3. Quality is the most sensitive criterion, followed by minimizes nuisance, aesthetics, feasibility and then costs.

Table H2: All possible K values within the boundary conditions

Pair of Alternatives	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics
A1 – A2	N/F	N/F	65535	-1733	-1376
A1 - A3	N/F	N/F	N/F	65535	N/F
A1 – A4	N/F	N/F	-405	65535	-3753
A1 – A5	N/F	N/F	N/F	N/F	N/F
A1 – A6	N/F	N/F	N/F	-1048	-1910
A2 – A3	N/F	N/F	N/F	N/F	N/F
A2 – A4	72	-153	N/F	-463	-503
A2 – A5	-286	N/F	N/F	N/F	N/F

A2 – A6	N/F	N/F	N/F	-519	65535
A3 – A4	N/F	N/F	N/F	N/F	N/F
A3– A5	92	N/F	-852	-908	-2400
A3 – A6	N/F	N/F	-531	N/F	N/F
A4 – A5	N/F	N/F	N/F	N/F	N/F
A4 – A6	N/F	65535	N/F	-495	-1233
A5 – A6	-11	33	-129	21	34

Table H3: Critical degree and Sensitivity coefficient for each criterion

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics
Critical degree	11	33	239	21	34
Sensitivity coefficient	0.09	0.03	0.004	0.05	0.03

Quality is the most critical criteria, followed by feasibility, aesthetics, costs and lastly minimizes nuisance.

Appendix H.2: Sensitivity analysis of alternatives

Next, the most critical measure of performance needs to be found. In this case, this is the score of the alternative to the power of the weight of the criterion, as described in the explanation of the WPM. The relative minimum change which must occur to the performance a_{ij} to change the current ranking between alternatives A_l and A_k is denoted with:

$/ \square i, j, k \square = \square i, j, k \square \times 100 \square a \square ij \square \square$, for 1 ≤ i, k ≤ M, and 1 ≤ j ≤ N. [4]

With:

$\square i, j, k \square$ = threshold value of a_{ij}, the absolute minimum change of a_{ij} to change the current ranking.

a_{ij} = the performance score

This threshold value is determined with the following boundary conditions:

$/ (i, j, k) > Q$, when i > k, or:
$/ (i, j, k) < Q$, when i < k.

With Q defined as:

$$Q = 1 - W(j) R(A(k), A(i)) \times 100 \quad [5]$$

Also, the boundary condition of the relative threshold value is:
$/ (i, j, k) \leq 100$ [6]

Table H4: Relative threshold values

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics	
A1	-631	-1281	-3733	-15481	-23631	A2
A1	-9045	-38694	-393915	-9514767	-2,5E+07	A3
A1	**-384**	**-702**	**-1703**	**-5384**	**-7556**	A4
A1	-5690	-21120	-170350	-2981966	-7037000	A5
A1	-1888	-5074	-23909	-197551	-371912	A6
A2	86	93	97	99	100	A1
A2	-1152	-2709	-10180	-60967	-104121	A3
A2	**34**	**42**	**53**	**65**	**68**	A4
A2	-692	-1437	-4347	-19039	-29554	A5
A2	-172	-275	-526	-1169	-1468	A6
A3	99	100	100	100	100	A1
A3	92	96	99	100	100	A2

A3	95	98	100	100	100	A4
A3	**37**	**45**	**57**	**69**	**72**	A5
A3	78	87	94	98	98	A6
A4	79	88	**94**	**98**	**99**	A1
A4	**-51**	**-72**	-113	-184	-210	A2
A4	-1788	-4736	-21753	-173405	-322940	A3
A4	-1096	-2545	-9353	-54279	-91814	A5
A4	-310	-545	-1232	-3504	-4759	A6
A5	98	100	100	100	100	A1
A5	87	93	98	99	100	A2
A5	**-58**	-83	-131	-219	-251	A3
A5	92	96	99	100	100	A4
A5	66	**76**	**86**	**93**	**95**	A6
A6	95	98	100	100	100	A1
A6	**63**	**73**	**84**	**92**	**94**	A2
A6	-360	-650	-1541	-4714	-6548	A3
A6	76	84	92	97	98	A4
A6	-191	-310	-610	-1409	-1792	A5

In Table F4, the relative threshold values can be found. The following equation finds the critical degree per alternative.

$/ \, i, j = \min k \neq i \; / \, i, j, k'$, for all M ≥ i ≥ 1, and N ≥ j ≥ 1. [7]

The sensitivity coefficient per alternative in terms of criterion C_j is:
$sens \, (a \, ij) = 1 \, / \, i, j$, for any M ≥ I ≥1, and N ≥ j ≥ i.

The critical degrees can be found in Table F5 and the sensitivity coefficient in Table F6.

Table H5: Critical degrees for each performance measure

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics
Alternative 1	384	702	1703	5384	7556
Alternative 2	**34**	42	53	65	68
Alternative 3	37	45	57	69	72
Alternative 4	51	72	94	98	99
Alternative 5	58	76	86	93	95
Alternative 6	63	73	84	92	94

Table H6: Sensitivity coefficient for each alternative in terms of the criteria

	Quality	Feasibility	Minimizes Nuisance	Costs	Aesthetics
Alternative 1	0.003	0.001	0.001	0.000	0.000
Alternative 2	**0.030**	0.024	0.019	0.015	0.015
Alternative 3	0.027	0.022	0.018	0.015	0.014
Alternative 4	0.020	0.014	0.011	0.010	0.010
Alternative 5	0.017	0.013	0.012	0.011	0.011
Alternative 6	0.016	0.014	0.012	0.011	0.011

The most critical alternative can be found with the following equation.

$/ \, Lk = \min M \ge i \ge 1 \;\; \min N \ge j \ge 1 \;\; / \, i.j$, for some N ≥ k ≥ 1.

In this case, this is alternative 2.

Appendix H.3: Calculations in Matlab

To speed up the process of performing the sensitivity analysis, a Matlab script has been created. This Matlab script can be found below. To check whether the Matlab script was correct, the examples from the paper of Triantaphyllou & Sánchez (1997) were inserted to verify the code.

```
%%Set up of the code

%Input:
% Crit = Scores the alternatives got per criteria
Crit = [1, 1, 4, 7, 7; 7, 3, 4, 3, 2; 10, 11, 7, 7, 9; 3, 6, 1, 7, 5;...
    5, 9, 9, 11, 11; 10, 6, 11, 1, 2]; % Row = alternative, column = criteria
l = 1;
Crit2= [];               %Create empty vector

while l<=6               %Amount of alternative
    for i = 1:5          %Amount of criteria
        Crit2(l,i) = Crit(l,i)./ max(Crit(:,i));  %Fill empty vector with normalized scores
    end
    l = l+1;
end

%Create Table with normalized scores
T = array2table(Crit2, 'VariableNames', {'Quality' 'Feasibility' 'Minimizes Nuisance' 'Costs' 'Aesthetics'}, ...
    'RowNames', {'A1', 'A2','A3','A4','A5','A6'});

%Calculate Performance score
P = 1;
j= 1;
Weight = [0.33, 0.25, 0.18, 0.13, 0.12];  %Weight of the criteria
Performance = [];           %Saves final performance score
PerformanceTable = [];      % Saves performance for each alternative per criteria


while j<=6                  % j = alternative
    for i = 1:5             % i = criteria
        P = P*table2array(T(j,i))^Weight(i);        %Calculate performance score per alternative
        PerformanceTable(j,i) = table2array(T(j,i)).^Weight(i);  %Calculate permance measures
    end
    Performance = [Performance;P];
    P = 1;
    j = j+1;
end
```

```
%Part 1 of sensitivity analysis: Finding most critical criterion
%Resetting variables
i = 1;
j = 2;
K_value = [];
Table2 = [];
% Finding the K values
while i<= 5
    while j<= 6
        for k = 1:5
            K_part1 =1;
            % Calculating the product for each of the criteria
            for y = 1:5 % y = criteria
                b1 = PerformanceTable(i,y);
                b2 = PerformanceTable(j,y);
                Wy = Weight(y);
                 K_part1 = K_part1 * ((b1/b2)^Wy);
            end
            % Calculating for the specific criterion
            Wk = Weight(k);
            a1 = PerformanceTable(i,k);
            a2 = PerformanceTable(j,k);
            K_part2 = log10(K_part1);
            K = K_part2/log10(a1/a2)*(100/Wk);
            K_value(k) = K;
        end
        Table2 = [Table2; K_value];
        j = j+1;
    end
    i = i+1;
    j = i+1;
end
%Removing the values that are not in line with the boundary conditions
Table2(Table2>100) =NaN;
```

Problem 2: Determining the most crititcal measure of performance

```
%Input:
i = 1;
k = 2;
y = 1;
C1 = [];
l = 1;       % row in Table
Table3 =[];
k_old = [];

while i <= 6
   while k <= 6
       if k ~= i
          for y = 1:5
             Wj = Weight(y);
             R = Performance(k)/Performance(i);
             Q = (1-nthroot(R,Wj))*100;
             Table3(l,y)=Q;
          end
       else
             l = l-1;       %Reset the l that was not used
       end
       l = l+1;             %Next row
       k = k+1;             %Next alternative (right side)
   end
   i = i+1;                 %Next alternative (left side)
   k = 1;                   %Start at A1 for the right side alternative
end
```

```
%Remove values that are not in line with the boundary conditions
Table3(Table3>100) =NaN;
%Calculate absolute values of Table3
absTable = abs(Table3);

% First, the minimum value per group of 5 rows in 1 column is found. The
% rows represent the alternative, and the column the criteria.

N_values = [1 6 11 16 21 26];       %The values at which the left-side alternative changes
Store = [];
Store2 = [];
Store3 = [];
x = 1;

% Calculate the critical degree
for n = 1:6
    while x<=5
    [c,ix] = min(absTable(N_values(n):5*n,x));
    ix = ix + (n-1)*5;
    Store = [Store; ix];
    Store2 = [Store2, c];
    x = x+1;
    end
    x=1;
    Store3 = [Store3; Store2];
    Store2 = [];
end

%calculate sensitivity coefficient
sens = ones(6,5)./Store3;
```