THE RE-USE OF BRICK FROM DUTCH POST-WAR HOUSING (1945-1970) IN THE CIRCULAR BUILT ENVIRONMENT

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ABSTRACT

Brick doesn't fit within the goal of the Dutch government to become fully circular by 2050. A lot of brick waste is produced, and the current 'recycling' option that turns it into road granulate doesn't compensate for the production. A large source of brick waste is Dutch post-war housing from 1945-1970. Therefore, the potential of re-using brick from this source is questioned. The research shows that bricks harvested from this housing type have the highest potential of being applied on new prefab façade elements and in the exterior space plan and exterior 'stuff' that requires durability and little flexibility. The bricks can be harvested with three harvesting techniques that are examined on their embodied carbon. The harvesting process is difficult as masonry in post-war housing is typically built with hard-cement mortar that doesn't allow for efficient separation of individual bricks. Nevertheless, a harvesting efficiency of up to 90% can be achieved when cutting existing facades into panels. For individual bricks, this efficiency can be as high as 50% through vibrational rasping.

KEYWORDS: *Brick, Urban Mining, Circularity, Construction Waste, Post-war housing*

I. INTRODUCTION

In 2016 the Dutch government has expressed the ambition to run on a fully circular economy by 2050. As the construction industry is responsible for 50% of the raw material consumption and produces approximately 40% of the country's total waste (Ministerie van I&M & Ministerie van EZ, 2016), a large shift needs to be made in this sector to reach the circularity goals.

Brick, the building material that has defined Dutch architecture for centuries currently doesn't have a strong position in this circular future. Stony material, including brick, makes up for the largest share (70%) of all the waste produced by the construction sector (Van Dijk, 2004). Currently almost all of this stony rubble is transformed into base-material for roads which is considered recycling since a 2015 change of law (Staatssecretaris van Infrastructuur en Milieu, 2015). Although this can be considered more rational than disposing it as landfill, it doesn't offer a long-term solution that can be part of the 2050 circular economy. The share of masonry rubble (35%) in the stony fraction is already enough to produce 155% of the required granulate for the Dutch road expansion plans until 2031 [1]. As typical road granulate can only contain up to 40% brick (Van Dijk, 2004), this surplus is even larger.

Through an analysis of the demolishing industry in the Netherlands it becomes clear that a large share of construction waste originates from post war housing from the period 1945 – 1970. The main reasons for this are the general lower quality of these dwellings, and the fact that the housing corporations who own the largest share of this type have a relatively high demolishing rate. (EIB & Metabolic, 2020). As brick is commonly applied in this dwelling type, a solution for reducing the amount of brick waste can potentially be found there. For this reason, this paper focusses on the

[1] Yearly construction waste = 25mton/year (TNO, 2018). Masonry fraction = 6,1 mton/year (Van Dijk, 2004). Road expansion plans until 2031 = 1000 km (Van der Aa, 2017). 1 mton rubble = 38 km 3 lane motorway (Van Dijk, 2004). Until 2031 (6,1 mton/year *11 year = 67,1 mton masonry rubble). 67,1 * 38 = 2550 km. 155% too much.

following research question: *How can bricks from Dutch post-war housing (1945-1970) be re-used in the circular built environment?*

This question focusses on re-using and not on recycling and preservation. Re-using is defined as reintroducing a product for the same purpose and in its original form (Ellen MacArthur Foundation, 2015). Options of recycling where bricks are brought back as crude feedstock are therefore not considered. In preservation, existing materials or components are repaired and maintained without adapting the function or location. Brick preservation options are not considered either because housing corporations generally don't primarily base their decision for demolition on the technical quality of the brick. This decision is mostly influenced by insulation and quality of the climate installations. A focus on preservation would therefore move the scope of this research to other aspects of the building, that on their turn influence the preservation of brick.

In order to structure the research into the re-use potential of the brick, the 3-step strategy on urban mining from GXN et al. (2018) is adapted. This strategy describes the process of reclaiming components from the anthropogenic stock. It consists of the steps inventorying, harvesting, and distributing. As the distributing step is not part of the scope of this research, it is replaced with circular application. Within these steps the following sub-questions are posed:

- ***(Inventorying)*** *What are the properties and quality of bricks applied in 1945-1970 Dutch housing and what is the potential influence of these properties on harvesting and re-use?*
- ***(Harvesting)*** *What is technical feasibility of reclaiming bricks from 1945-1970 Dutch housing and what is the environmental impact?*
- ***(Circular application)*** *What methods can be used to re-apply the harvested brick in the circular built environment and what type of building components can be made?*

II. METHOD

The *inventorying* will be done by consulting historical literature and NEN building codes. By doing so, an understanding of the properties of brick applied in housing from 1945-1970 will be obtained, as well as the influence of this properties on the harvesting potential. The desired result of this inventory will be an assessment diagram that provides a structured overview of the properties.

The *harvesting* step will be investigated through case-study research. All the known methods of brick harvesting will be assessed on the degree of circularity in a quantitative way by researching their output efficiency and energy used in the process. The data on output efficiency will be obtained through literature on the specific harvesting methods. The data on energy used in the processes will be expressed through the amount of embodied carbon that is 'added' to the brick through the harvesting and processing ($KgCO_2$/kg input). This way, the environmental effectiveness of recycling can be determined. This data will be retrieved in a *cradle-to-gate* process, where the demolition site is considered the cradle and the gate. Therefore, the carbon footprint of transportation is not included. The data on the carbon footprint presented in this paper is retrieved from the Inventory of Carbon & Energy by Hammond and Jones (2011).

In the last chapter the *circular application* of the harvested bricks will be researched by analyzing the environmental impact of transforming these bricks into a 100 m^2 masonry wall. The carbon footprint will be assessed by researching the carbon footprint of the materials required to make this transformation. Next, the best method of re-applying the brick in a circular way will be research through categorization with the Shearing Layers of Change by Brand (1994). A circular application is defined as an application that is functional and made of optimum materials to deliver the best performance, while minimizing its negative impact along the whole life cycle. (Fifield & Medkova, 2017). Two criteria of circular design defined by RSA (2014) are used to assess the circularity of brick application options. These are; *Design for Longevity* and *Design for Material Recovery.*

III. INVENTORYING BRICK FROM DUTCH POST-WAR HOUSING

In a typical urban mining process, an inventory is made to determine the availability and reusability of a building or a specific material. There are two methods of inventorying; through estimation and through thorough inspection(GXN et al., 2018, p.23). Inventorying through estimation is done without inspecting specific buildings, but with the use of data and key-figures. The second method, inventorying through inspection, is done through a precise evaluation of a building or material. Through counting, measuring and testing an exact assessment of an element can be made. In this evaluation the impact of material properties on the harvesting and re-use potential should become clear.

Evaluation through thorough inspection is always required when re-using a material, but a number of properties from brick can be pre-determined as it has historically been a standardized building component bound by regulations. Although the quality of a brick is much dependent on the properties of the clay used and the baking process (Stenvert, 2012), the measurements of the single brick and wall build up are mostly consistent within a certain period.

3.1. Environmental impact

An important aspect in the process of urban mining is asking the question if it is environmentally beneficial to re-use a material, instead of producing from virgin material. In the selection of building components for re-use, the focus should be placed on materials with a high embodied energy, as they have the largest potential impact. These are materials like metals, plastics and bricks (Gorgolewski & Morettin, 2009, p.108), as well as the broader range of stony materials (TNO, 2018, p.21)

In the cradle-to-gate process of brick production in the Netherlands different steps take place that have a varying environmental impact. The river clay that is used to produce bricks in The Netherlands can theoretically be considered a renewable source as the clay extraction is compensated by the clay deposition (Van der Meulen et al., 2009, p.1). The baking process of the brick requires a high-amount of energy, as they are baked at temperatures between 950º C and 1150º C for 6 hours using fossil fuel (Hildebrand, 2014, p.128).

Although the environmental impact of brick is relatively low compared to materials such as aluminum and steel, the large quantities of brick applied in the Dutch building stock result in a relatively large overall environmental impact. Because of its large volume, the total amount of brick in the Dutch stock has a larger environmental impact than the total amount of aluminum (TNO, 2018, p.20).

3.2. Dutch brick measurements

Determining the measurements of bricks in a building that will be used as a source for urban mining is important for the re-use stage of the bricks, because it tells an architect or contractor what he's working with (GXN et al., 2018, p.23). It can potentially influence the decision to harvest material from one building or the other, because different bricks were used.

Generally, the differences in the most commonly used brick sizes in the Netherlands are relatively small. For bricks used in Dutch post-war housing, the 1934 NEN520 regulation applied, that described the maximum tolerances of the most used brick types in the Netherlands (Stenvert, 2012)[2]. The three different types of brick presented in this regulation were the *Waalformaat , Vechtformaat and Rijnformaat* brick as displayed in figure 1. In 1976 the NEN520 was replaced with the NEN2489 where smaller tolerances were used within different classes. Within these three types the Waalformaat brick was and is the most frequently used type (Stenvert, 2012).

Waalformaat (mm)	**Vechtformaat (mm)**	**Rijnformaat (mm)**
208-220 x 101-107 x 52-56	208-220 x 101-107 x 40-44	175-187 x 84-90 x 44-48

Figure 1 - Typical measurements of brick in applied in Dutch post-war housing (1945-1970)

[2] In his book, Stenvert mentions that the NEN520 originates from after WWII, but the actual publishing date is 1934. Through email correspondence with Stenvert he acknowledges that it was indeed published in 1934 but as the rule was only used again after the war, the same principle applies.

Because the tolerances in the bricks are relatively small, an estimation of the sizing of a large batch of bricks from the same building can be made relatively easy. Depending on the demolishment technique used, the harvesting of bricks can lead to a larger tolerance because of damage inflicted on the brick. Therefore, the exact measurements (within tolerances) of a batch of bricks should be examined after harvesting.

3.3. Dutch brick quality

Evaluating the technical quality of harvested bricks is important for the re-use phase. The original quality of bricks from 1945-1970 housing was most likely described in the NEN520[3]. Any bricks that are planned on being used in new applications where the brick quality is important should be subjected to testing according to the latest specifications described in the NEN-EN 771-1:2011. This way the quality of the brick is ensured and it can be safely used in new projects. Beyond the technical quality, the aesthetical quality of bricks should be considered. Many people believe that the natural patina of re-used bricks is more attractive than brand new bricks (Hildebrand, 2014, p.395). This is a factor that can be exploited to promote the re-use of brick.

3.4. Mortar type

The mortar that is used to transform bricks into a masonry wall can typically be divided into two categories: traditional lime mortars and modern cement mortars (Addis, 2006). Traditional lime mortar is softer than cement mortar and has a weaker connection to the brick, making it easier to separate them. Modern cement mortar is often stronger than the brick itself and has a very strong connection with the brick, making it difficult to separate individual bricks.

Housing made in the period 1945-1970 is very likely to be made with modern cement mortar. After the invention of Portland cement in 1824 lime mortar was quickly superseded by this stronger and more efficient version that allowed for quicker building and less vulnerability in the building process (RCE, 2003). As post-war housing was focused on rapidly building a lot of houses, it is almost certain that cement mortar was the standard.

As the bond between modern cement mortar and brick is so strong, cracks caused by building or foundation movement are more likely to run through the brick instead of being absorbed by the mortar as would happen with lime mortar (Addis, 2006). The prevention of cracking in brickwork facades was initiated in 1976 with regulations that advised for the use of expansion joints (Wingender, 2016). The buildings in the context of this paper (1945-1970) are therefore probably made without the use of expansion joints, and have a higher probability of showing cracks in the brickwork.

3.5. Wall type

Determining the specific construction of a masonry wall is important for both the harvesting and re-use stage of urban mining. There are two types of masonry constructions; load-bearing and non-load-bearing. Any masonry used in a building with a structural frame of concrete, steel or timber is generally speaking non-load bearing. (Addis, 2006). If a masonry wall is load bearing, the sequence of harvesting should be well considered, as the structural integrity of the building is changed during the process.

Historically, most walls in the Netherlands were made of solid, load-bearing brick. Although non-load-bearing cavity walls were already occasionally applied in the 17th century (RCE, 2013), the cavity wall started appearing on a larger scale after 1900 to tackle the problems of moisture and insulation. Only in 1960 the cavity wall was made obligatory for brick constructions trough the Model Building Regulation (Wingender, 2016). Therefore, a clear demarcation can be drawn in housing made in the period 1945-1970. Brick housing made after 1960 will definitely have a cavity wall, whereas housing prior to that year may not have a cavity wall and could be built with solid brick walls.

[3] NEN doesn't hold the document anymore due to the bad physical condition. The document has never been digitally recorded.

The addition of insulating material in cavity walls appeared in 1975 when restrictions in the Model Building Regulation demanded a higher Rc value of exterior walls. All housing from the period 1945-1970 is therefore most likely built without cavity-wall insulation. There's a probability that insulation has been added afterwards. In the second half of the 1970's insulation was added in an estimated 1,5 million homes, and is still going on nowadays (Van der Linden, 2015). The use of specific types of cavity wall insulation can affect the harvesting of bricks. Walls insulated with chemically expanding insulation materials like PUR, are harder to disassemble and may require additional cleaning before the bricks can be re-used.

3.6. Evaluating tool for case studies

The information that has been described in this chapter on the evaluation of brick properties is summarized in figure 2. This diagram is purposed as an evaluation method for *inventorying through estimation.* General properties of masonry constructions from housing projects dating from 1945-1970 can be assessed with this diagram.

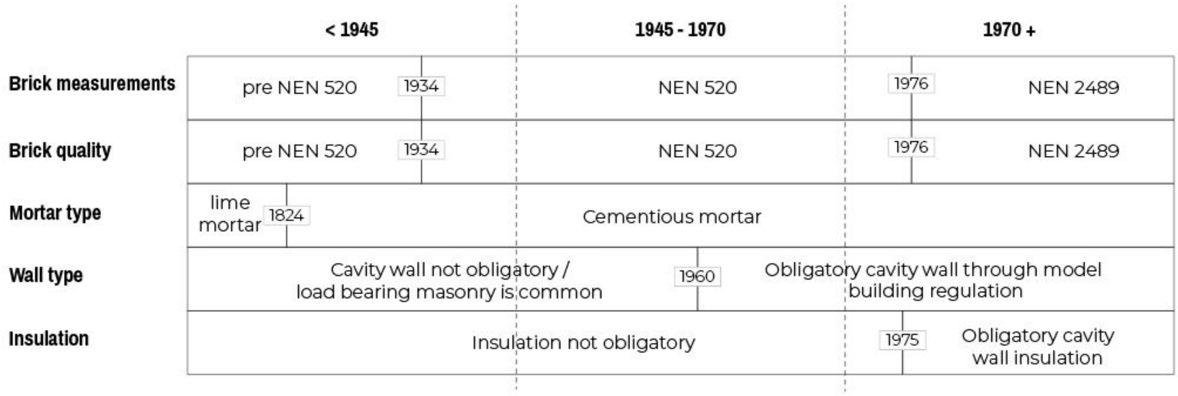

Figure 2 - Inventorying diagram for the properties of brick(work) from Dutch post-war housing (1945-1970)

IV. Harvesting Brick from 1945-1970 Dutch housing

The harvesting stage describes the process of retrieving bricks from buildings. In this stage material knowledge and material assembly knowledge is required to make building components usable in the next stage (GXN et al., 2018, p.25). This chapter describes three brick harvesting techniques, and assesses them on the type of output, output efficiency and the embodied carbon (kgCO_2) of the process. The output efficiency is considered the share of bricks from the original building that can be CE marked. The remaining share of the brick is assumed to be discarded in a traditional way by transforming it into road granulate. A visual overview of the harvesting techniques is included in appendix A. The data on embodied carbon is retrieved by seeing the different harvesting techniques as *cradle-to-gate* processes. Therefore, the demolition site is seen as the cradle and the gate, and the carbon footprint of any transportation is not included.

The harvesting techniques *vibrational rasping* and *thermal separation* start off with a 'standard demolition' process. In this process the masonry walls are scraped off the building by an excavator and collected from the ground (Gustafsson, 2019, p.30). The embodied carbon of the demolition of ceramic brick masonry through standard demolition is estimated at 0.00247 kgCO_2/kg (Caldas et al., 2017, p.77). The embodied carbon of electric energy spent in the harvesting processes is assumed to be 0 kgCO_2, as it is context specific. The electric energy can either be won through renewable methods, or with fossil fuel.

4.1. Vibrational Rasping

Vibrational Rasping is a harvesting technique that starts off with a standard demolition process, where extra caution is taken into not driving on the bricks with the vehicles on site[4]. The chunks of brick waste are then transported to a processing plant, where they are separated and cleaned from mortar using vibrational rasping (Goodsite & Juhola, 2017, p.224). The machines used in this process run on electric energy and no water or chemicals are used for the cleaning of the bricks (Gamle Mursten Aps, 2013, p.3) An average 50% of the bricks from a building can be retrieved using this technique. The bricks processed this way are subjected to testing according to EN 771-1:2011 and are CE stamped. With this CE stamp the bricks are therefore considered new. As the process of vibrational rasping is done with machinery running on electric energy, the embodied carbon is assumed to be 0.00247 $kgCO_2/kg$ input, caused by the standard demolition process.

Method	**Output**	**Output efficiency**	**$KgCO_2/kg$ input**	**Energy used (cradle to gate)**
Vibrational Rasping	Single bricks	50%	0,00247	Standard demolition = Fossil fuel, Vibrational rasping = Electric energy

Figure 3 - Overview of the properties of the harvesting technique 'Vibrational Rasping'

4.2. Cutting panels

The Danish architecture firm Lendager Group re-uses bricks from old buildings by cutting $1m^2$ panels from the façade and reusing these panels in a new project (Gorgolewski, 2018). With this technique brick walls made with cement mortar can be harvested more easily and efficient, as no effort is put into trying to separate individual bricks from the mortar. The efficiency of this process depends on the quality of the masonry and the desired size of the panels. Lendager Group used 1 m^2 panels as this allowed for a harvesting process by two construction workers, and efficient transportation where 4 panels would fit on an EU sized pallet (Gustafsson, 2019, p.16). The cutting panels technique can be applied on both half-stone and full stone walls, as the typical circular saw used in this process can have a sawing depth of up to 400mm. Full stone waalformaat walls have a thickness of 210 mm. As the process of cutting the panels from the façade is done with machinery running on electric energy, the embodied carbon is assumed to be 0 $kgCO_2/kg$ input.

Method	**Output**	**Output efficiency**	**$KgCO_2/kg$ input**	**Energy used (cradle to gate)**
Cutting panels	Brick panels	90%	0	Cutting panels = Electric Energy

Figure 4 -Overview of the properties of the harvesting technique 'Cutting Panels'

This harvesting technique is more suitable for the application on brick walls made with cement mortar. As lime mortar has a weaker connection to the brick, it is more likely that the structural integrity of the panel is weakened after it is been removed from the wall. As mentioned in paragraph 3.4, cracks in masonry built with lime mortar, will generally run through the mortar. As the connecting element of the bricks is therefore weakened, the structural capacity of the cut panel will therefore be less.

4.3. Thermal separation

Thermal separation is a harvesting technique that starts off with conventional demolition techniques. The rubble is transported to a processing plant where the brick chunks are heated in a gas kiln at 540º C for approximately 3 hours (Van Dijk, 2004). As brick and cement mortar have a different expansion coefficient, their bond is broken at this temperature. An average 40% of the bricks from a building can be retrieved using this technique (TNO, 2018, p.35). As no information on the energy use of this process is known, the embodied carbon of the thermal separation process is roughly estimated at 0,099 $kgCO_2/kg$ input. The supporting calculation is added in appendix B.

[4] C.J.Nielsen (personal communication, April 14, 2020)

Method	Output	Output efficiency	$KgCO_2$/kg input	Energy used (cradle to gate)
Thermal seperation	Single bricks	40%	0,00247 + 0,066 = 0,068	Standard demolition = Fossil fuel, Thermal seperation = Fossil Fuel

Figure 5 - Overview of the properties of the harvesting technique 'Thermal Separation'

This process is not suitable for masonry walls built with lime mortar, as lime mortar is much softer and follows the expansion of the brick (Van Dijk, 2004). The harvesting efficiency of thermal separation applied on full-stone brick walls is expected to be higher than the harvesting efficiency of vibrational rasping applied on full-stone brick walls. Large full-stone brick wall chunks can be placed inside the gas kiln without having to separate the bricks first.

V. RE-USING BRICKS IN THE CIRCULAR BUILT ENVIRONMENT

The last step in the urban mining strategy is the re-use of the harvested brick. Based on the harvesting methods presented in the previous chapter two types of brick re-use can be distinguished; separate brick re-use and brick panel re-use. In this last chapter different methods are analyzed that can be applied to re-use the components from these two methods in a new building.

In order to make the re-use methods comparable, they're analyzed within the theoretical case where a 100 m^2 waalformaat half-brick masonry wall (10 mm mortar) is harvested and re-assembled. The three methods are assessed on sum of the embodied carbon of the harvesting process and the embodied carbon of extra required material to rebuild the wall. As a comparison, the embodied carbon of a 100 m^2 brick wall made with only virgin material is included as a baseline. The results are displayed in figure 6. The detailed flow diagrams for the re-use methods is included in appendix C.

Method	Harvesting Efficiency (η)	Reduced brick waste (kg)	total CO_2 emission of harvesting (kgCO2)	ECO_2 of extra required brick (kgCO2)	connector	ECO_2 of connector (kgCO2)	Total ($KgCO_2$)	compared to new brick
New bricks (baseline)	n.a.	0	n.a	3260	10 mm cement mortar	332	3593	n.a
					10 mm lime mortar	294	3555	n.a
Vibrational Rasping	50%	7410	37	1630	10 mm cement mortar	332	1999	-44%
					10 mm lime mortar	294	1961	-45%
Thermal Seperation	40%	5928	1015	1956	10 mm cement mortar	332	3303	-8%
					10 mm lime mortar	294	3265	-9%
Cutting Panels	90%	13338	0	326	100 mm concrete backing	2990	3349	-7%
					50 mm concrete backing	1495	1854	-48%
					Steel U frame (50x50x5mm)	2618	2977	-17%

Figure 6 -Assessment of the embodied CO_2 of the built & rebuilt of a 100 m^2 brick wall, using three brick harvesting techniques.

5.1 Separate Brick re-use with mortar

Separate brick re-use is focused on the re-use of brick resulting from the harvesting methods *Vibrational Rasping* and *Thermal Separation*. In order to transform these bricks into a masonry wall, a connecting element is required. In the conventional construction industry, cement mortar would be the primary solution. The downside of this approach is the relatively high embodied energy of Portland cement, and the strong bond with the bricks that make it difficult to separate them in a later end-of-life stage. Lime mortar is considered a more circular connector, because the weaker bond allows for an easier separation of the bricks. The downside of chalk mortar is the lower drying time and vulnerability during the construction process (KNB, 2018). The embodied CO_2 of chalk mortar (0,189 $KgCO_2$/kg) is slightly lower compared to cement mortar (0,213 $KgCO_2$/kg)(Hammond & Jones, 2011).

From the data in figure 6 it can be concluded that carbon footprint of the material in a 100m2 masonry wall can be reduced by up to 45% through the use of re-used separate bricks. The table also shows that there is a relatively small difference in embodied CO_2 between lime mortar and cement mortar. In the circular built environment, the use of lime mortar is preferred as it allows for a more efficient process of separating the brick and mortar in the future.

5.2 Separate Brick re-use with new techniques

Alternative upcoming solutions for the built of masonry walls are dry connection systems that can be completely demounted from the brick. A brief analysis of circular masonry wall construction techniques that are currently on the market is made. Through an online search in Google made in April 2020, five demountable brick connection systems were found; *Facadeclick, Fixbrick, Clickbrick, Drystack* and *LeeBrick.* Images of these systems can be found in appendix D.

Each of these systems uses a customized brick. Therefore, these adjustments also have to be made on a re-used brick for the system to work. In the *Facadeclick* and *FixBrick* system, the adjustments to the brick are made before the baking process, and are therefore not suitable for the application on re-used brick. In the other *ClickBrick, Drystack and Leebrick*, the adjustments are made after the baking process, so they could theoretically be applied on re-used brick. From these three systems, the *ClickBrick* and *LeeBrick* system both make use of extruded bricks. This type of brick is mechanically extruded through a mold, resulting in a very smooth and even surface (KNB, , p.6). As the surfaces are very smooth, they're used to align the brick to a saw that cuts a groove into the brick. As a smooth surface is not likely on a re-used brick. Applying the *ClickBrick* and *LeeBrick* method on re-used bricks would therefore most likely lead to problems were the groove is not aligned between bricks.

The *DryStack* system uses molded bricks that have a higher tolerance in sizing in comparison with extruded bricks. The connectors are inserted into 8 holes that are drilled into the brick. These connectors have a relatively large tolerance in the vertical direction, and would potentially be able to compensate for irregularities in the surface of a brick. For this reason, the The *Drystack* system has the highest theoretical potential of being applicable on re-used brick. Physical testing in additional research is required to test this hypothesis.

5.3 Brick panel re-use

As described in chapter 4.2 masonry walls can be re-used by cutting them into $1m^2$ sized brick panels. This theory has been brought into practice by the Danish architecture firm Lendager Group. In order to transform the $1m^2$ brick panels into components that can be applied on a new building, they can either be casted in 100 mm concrete, or connected to a steel frame (Lendager Group, 2018).

In figure 6, the theoretical case where a $100m^2$ masonry wall gets harvested and re-assembled is analyzed for this technique. In this case it is assumed that 90% of the original brickwork can be harvested. The technique is analyzed for both the concrete backing and the steel frame. The figure shows that the embodied carbon of both of these connectors is very high. With the 100 mm concrete backing that Lendager Group applied, the embodied carbon of the panel is 8% smaller than new brick. It is questionable if the thickness of the concrete backing is actually structurally required and if it can be decreased to minimize the environmental impact. By using a 50 mm backing instead of a 100 mm backing, the embodied carbon is drastically lower (-48%), so it has a large impact.

The exact dimensions and weight of the steel frame are unknown, because it has never been applied in practice. Based on concept drawings by Lendager Group (2018), an estimation is made. This calculation is included in appendix E. As steel has a very high carbon footprint, the total reduced carbon footprint in comparison with new brick is smaller than the alternative with concrete (-17%). In comparison with the concrete backing, the steel frame is more circular when looking at the demountability. The wet connection between the brick and the concrete will be difficult to separate, whereas the connection with the steel frame can most likely be built with dry connections. Using the steel frame therefore has a lower carbon footprint over multiple lifecycles, if the same frame is used.

5.4 Circular application methods

Brick is a very versatile material that can be applied in a lot of ways. To ensure the circularity of these applications, the focus of these applications is placed on *Design for Longevity* and *Design for Material Recovery* as defined by RSA (2014). In this case, Design for Longevity is focused on design that allows for a long live through functional flexibility. When the functional flexibility of a building or component is low, renovation, demolition and rebuilt is often required, leading to a high use of virgin material and construction waste. Design for Material Recovery is focused on the demountability of a building or component. The demountability of a building component is important in the circular economy because it allows for re-use and recycling. The purity of a material is essential for high quality recycling (Hildebrand, 2014, p.379). Therefore, dry and demountable connections are preferred.

Using the shearing layers of Change by Brand (1994), as displayed in figure 7, a reflection on the circular application of brick that allows for *Longevity* and *Material Recovery* is made.

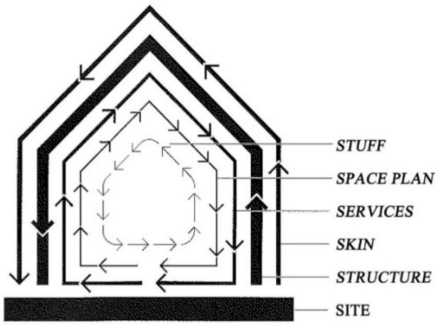

Figure 7 - Layers of Brand, adjusted by Jensen & Sommer (2018)

Structure

The load bearing structure of a building generally represents a large proportion of the total mass (Addis, 2006) and has a high environmental impact. It is therefore important that the structure has a long-life span and can be disassembled and re-used. Besides that, it is important that the load bearing structure allows for lay-out changes over time. Skeleton structures therefore shows strong benefits (Hildebrand, 2014 ,p. 380). Although it is theoretically possible to apply re-used brick in a new load bearing structure, it doesn't have a large potential in terms of material use, flexibility and demountability. The general challenge of applying re-used brick is guaranteeing the structural performance. In general, masonry load bearing structures are very bulky. For vertical loads, brick structures require the highest amount of embodied energy (Hildebrand, 2014 ,p.385). Masonry load bearing structures built with re-used brick will require even more mass, as the structural performance off re-used brick will be less exact. The uncertainty in structural capacity will be compensated by high safety factors in the structural calculations, leading to a higher material use (KNB, 2017b, p.7).

The functional flexibility of a building with a masonry load bearing structure is generally low, as the load bearing walls don't allow for lay-out changes. The demountability on the level of the brick is poor, as cement mortar will conventionally be applied as the connection system. Lime mortar would have a higher demountability potential but is very labor intensive. There are no known dry masonry connection systems for structural applications.

structure (50+ years)		potential	re-used brick structure
circularity criteria	Design for longevity	--	doesn't allow for functional flexibility.
	Design for material recovery	--	Poor demountability of load bearing brick.

Figure 8 - Summary of the circular application potential of re-used brick in the load bearing structure

Skin

As facades are exposed to exterior conditions, they require renovation and will most likely be changed one or multiple times (Jensen & Sommer, 2018,p. 68). Therefore, it is essential that these changes can be easily made. Non-load bearing facades allow for this adaptability (Hildebrand, 2014,p. 394). The application of heavy materials in the façade requires generally requires a large substructure, that are typically made of high-embodied energy materials like metal.

In terms of building flexibility, masonry has a high potential for being applied as the non-load bearing exterior leaf of a cavity wall. As brick is a very durable material, these facades typically require little maintenance. To ensure the flexibility of such a façade, they're ideally split up in larger prefab elements. These elements can be created through the *cutting panels* technique, or by incorporating separate bricks in prefab façade modules. To ensure the demountability of these prefab elements, dry connections should be applied between the different layers of the element. On the level of the brick, the demountability should be ensured through the use of lime mortar instead of cement mortar. As mentioned in chapter 5.2, the application of dry connection systems has potential, but requires additional research.

An alternative for applying brick as the non-load bearing exterior leaf of a building is applying it as a full-stone self-load bearing exterior leaf. This structure doesn't require structural connections with the inner leaf of the cavity wall as it accounts for its own stability. Hence, thermal bridges and the use of steel connections are reduced to a minimum (KNB, 2017a). The difference between the two types is the thickness; half-stone and full-stone.

Skin (30+ years)		**potential**	**re-used brick skin**
circularity criteria	Design for longevity	++	Brick = durable. Brick skin can allow for functional flexibility
	Design for material recovery	+	highly demountable façade panels can be created. The demountability on brick level is less.

Figure 9 - Summary of the circular application potential of re-used brick in the building skin

Space plan

A building should be flexible in use to prevent the demolition of a building because its functionality doesn't meet the standards anymore. Flexibility in the partition walls is the keystone to achieve this (Jensen & Sommer, 2018). Interior walls that don't carry loads should be installed as lightweight constructions (Hildebrand, 2014,p. 376) Applying brick for interior walls doesn't have a large potential in this sense because brick walls are heavy and don't allow for easy adaptation. Brick interior walls are typically connected to the building structure with mortar, and therefore require demolition when a function change is required.

Brick has a good potential in being applied in the 'exterior space plan' exposed to weather conditions as it is a very durable material. The exterior place plan, that for example can be created with exterior partition walls and paving is generally not changed frequently.

Space plan (10+ years)		**potential**	**re-used brick space plan**
circularity criteria	Design for longevity	+/-	Doesn't allow for flexibility in the interior space plan. Durability of brick for outside furniture is a plus.
	Design for material recovery	-	Interior brick walls are typically connected with floors by wet connections.

Figure 10 - Summary of the circular application potential of re-used brick in the space plan

Stuff

In the Layers of Brand, 'stuff' is something that changes frequently, represented by the thin line in the diagram. As brick is a heavy material, it is not suitable for the application in elements that allow for this rapid change, like privately owned interior furniture. Exterior stuff, or public street furniture, on the other hand requires less flexibility, and the durability of the brick is suitable for outside conditions. The functional flexibility of street furniture should be ensured by making the components movable. Wet connections with concrete foundations should therefore be prevented. The demountability of the bricks should be ensured through the use of lime mortar instead of cement mortar. As mentioned in chapter 5.2, the application of dry connection systems has potential, but requires additional research.

Stuff (1+ years)		**potential**	**re-used brick stuff**
circularity criteria	Design for longevity	**+/-**	Flexbility of interior furniture is low. Durability of brick for outside furniture is a plus.
	Design for material recovery	**+/-**	Interior brick walls are typically connected with wet connections.

Figure 11 - Summary of the circular application potential of re-used brick in 'stuff'

VI. Conclusions

The goal of this research paper is to find an answer to the question: *How can bricks from Dutch post-war housing (1945-1970) be re-used in the circular built environment?*

Using the definitions from the Layers of Brand, it can be concluded that harvested bricks from Dutch post-war housing have the most suitable circular application within larger modules in the skin of a new building. Besides that, they can be well applied in the exterior space plan and in exterior 'stuff' that requires durability and little flexibility. To ensure the circularity of these applications, dry connection systems should ideally be used between larger modules and between individual bricks. As these systems between re-used brick don't exist yet, lime mortar should be used instead of cement mortar. Lime mortar has a weaker connection with the brick, and allows for a more efficient disassembly and recycling process. The application of re-used brick in the load bearing structure of a building is not suitable, as brick load bearing walls don't allow for functional flexibility of the building. Besides that, brick load bearing structures generally use a lot of material and have a high embodied-energy. The application of relatively heavy brick in the interior space plan is not sensible, as the space plan should be flexible through the of use light-weight partition walls.

The harvesting of brick from post-war housing can be executed through three methods that are known on the market right now; *vibrational rasping (VR), cutting panels (CP) and thermal separation (TS)*. As post-war housing is generally built with hard cement mortar, it is difficult but not impossible to separate the individual bricks. VR and TS result in separate bricks, and CP results in brick panels that can be transformed into building components. The described techniques can be both applied on cavity brick walls and load-bearing walls, that are both common in post-war housing until 1960. Compared to the use of new virgin brick, the environmental advantage in terms of embodied CO_2 can be the highest (-48%) if CP is applied with a concrete backing of 50 mm. A thinner concrete backing would increase this number, but it is unknown if this is technically possible. VR has an environmental advantage of (-45%) followed by TS with (-9%). The impact of TR is relatively low, as the process of thermal separation runs on fossil fuel, whereas VR and CP run on electric energy. Generally speaking, the harvested bricks form post-war housing will have sufficient quality to re-use them for the above described functions. Stamping harvested bricks with a CE mark, that ensures the quality, is common practice.

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APPENDIX A - visual overview of harvesting techniques

Vibrational rasping

Image retrieved from: https://www.youtube.com/watch?v=dxT-GWepERfI

Image retrieved from: https://www.youtube.com/watch?v=KjaJa-iZaxA

Cutting panels

Image retrieved from Gorgolewski (2018)

Image retrieved from https://lendager.com/en/architecture/resource-rows/

Thermal seperation

Images retrieved from Van Dijk (2004). Higher resolution media not available.

APPENDIX B - Estimation of the embodied energy of Thermal seperation

In the process of thermal separation, bricks are heated at 540º C for approximately 3 hours. To estimate the embodied carbon of this process, it is compared with the production process of a new brick, as both of these processes require high temperature heating in a gas kiln.

The cradle-to-gate embodied energy of new bricks is 0,22 kgCO2e/kg (Hammond & Jones, 2011). In the production of a new brick, clay is heated at 950º C for 6 hours (Hildebrand, 2014) As this is a very energy intensive process, approximately 90% of the embodied carbon of a brick derives from this process (Hotza & Goulart de Oliveira Maia, 2014, p.449).

Therefore, the assumption is made that (0,22 kgCO2e/kg * 0,9 = 0,198 kgCO2e/kg) is accounted for in the baking process.

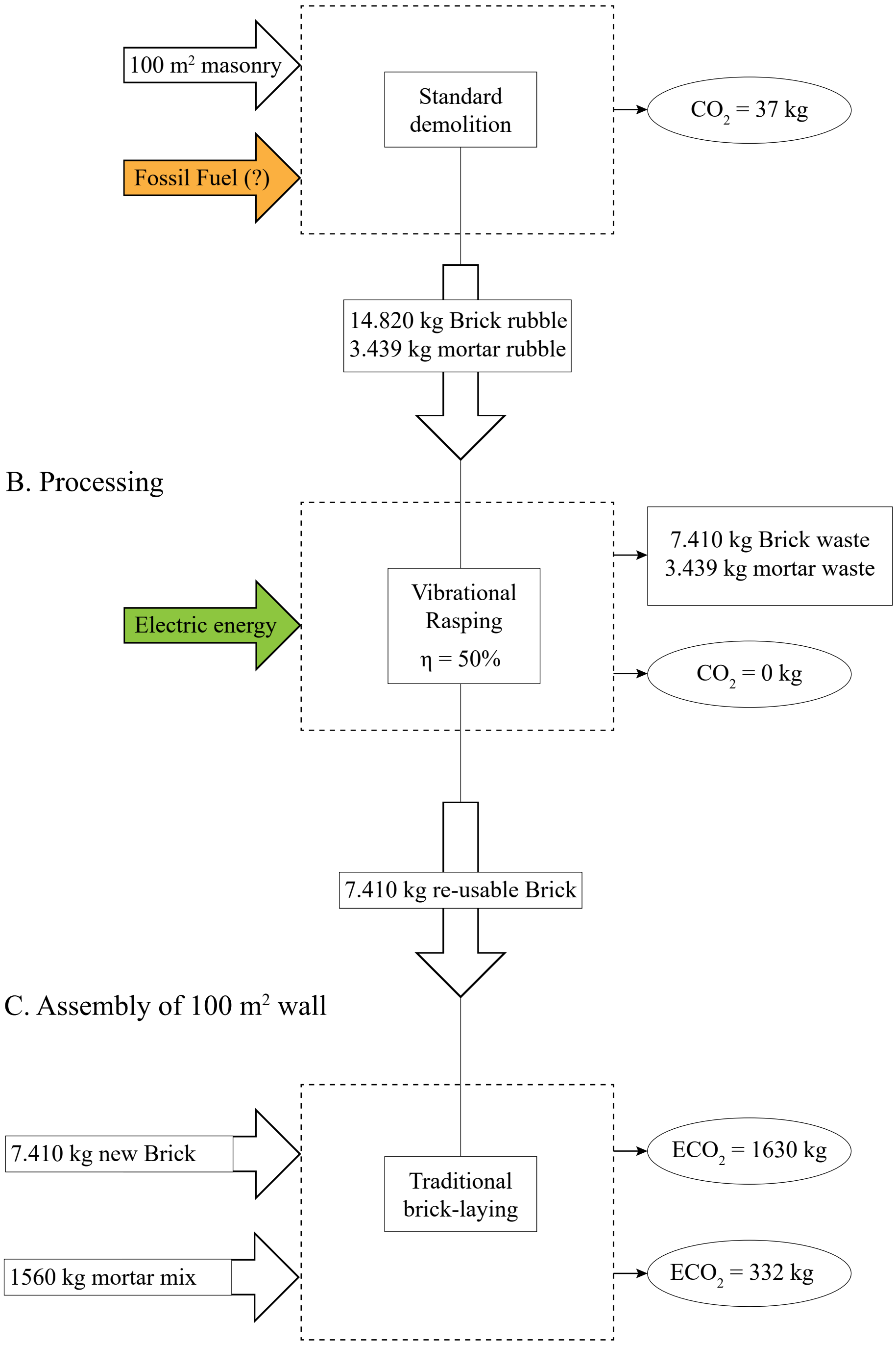
Compared to the baking of a new brick, thermal separation runs at half the time and half the temperature (6 hours at 950º C vs. 3 hours at 540º C). The assumption is made that the temperature in the oven and the usage of natural gas don't have a linear relation, as the heat loss is increased at higher temperatures. Therefore, it is assumed that the embodied carbon of thermal separation can be calculated by dividing the embodied carbon of the baking process of a new brick by 3 (0,198/3 = 0,066 kgCO2e/kg).

APPENDIX C - waste & embodied carbon analysis of harvesting and rebuild methods

Vibrational Rasping

Waste & embodied carbon assesment resulting from the harvestiging and rebuilt of a 100 m2 half-stone brick wall

A. Harvesting



Summary

Demolition and re-assembly of 100 m² single layer waalformaat brick wall

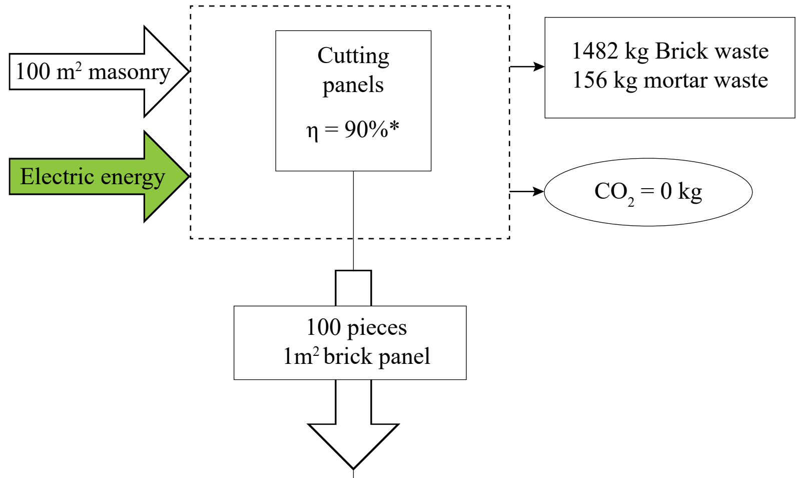
Reduced brick waste = 7.410 kg

ECO_2 of extra required material = 1.962 kg

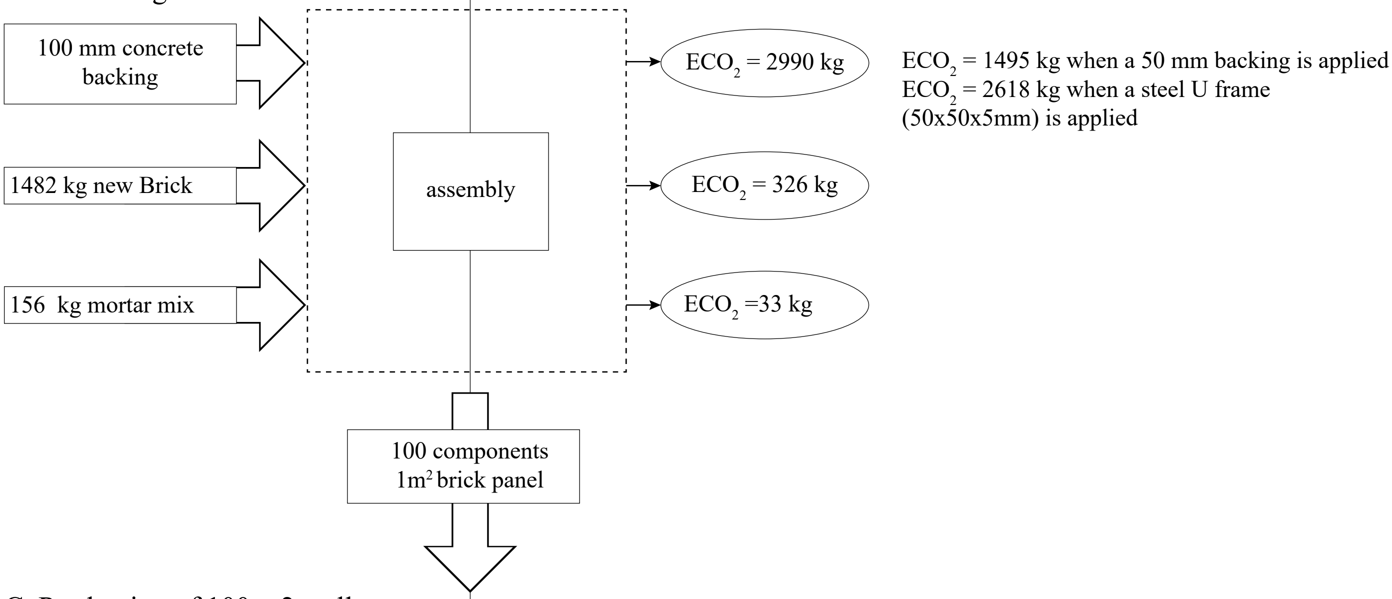
Cutting Panels

Waste & embodied carbon assesment resulting from the harvestiging and rebuilt of a 100 m2 half-stone brick wall

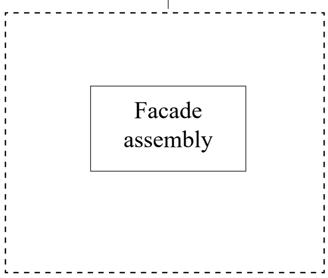
A. Harvesting



B. Processing



C. Production of 100 m2 wall



Summary

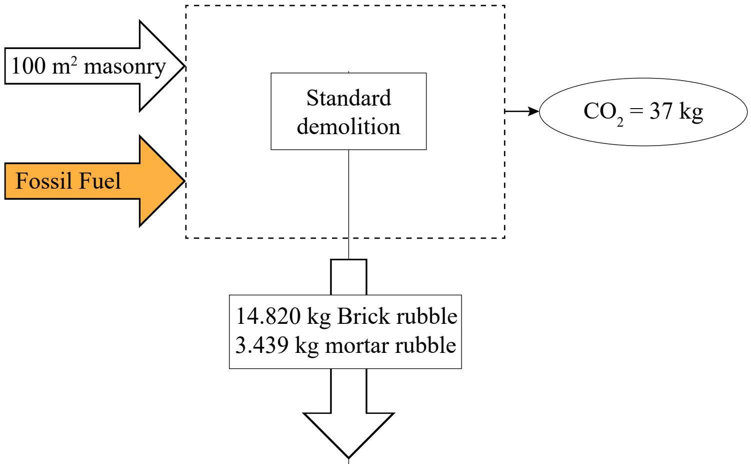
Demolition and re-assembly of 100 m2 single layer waalformaat brick wall

Reduced brick waste = 13.338 kg	ECO2 of extra required material = 3.349 kg

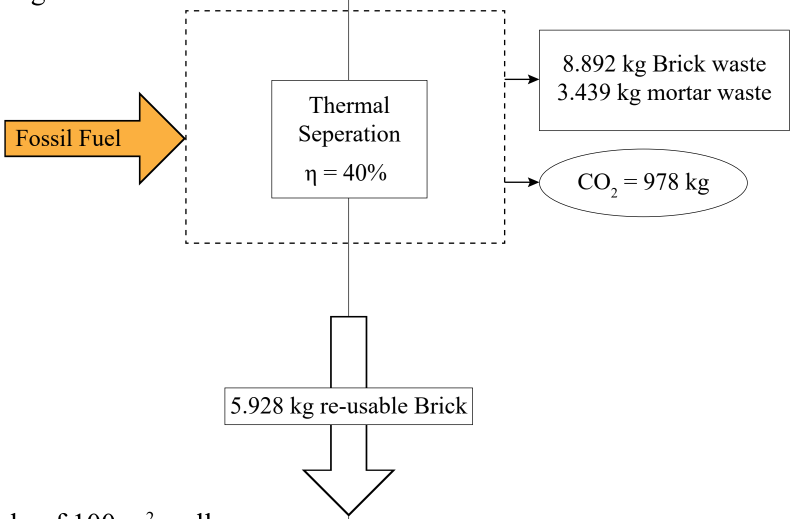
Thermal Seperation

Waste & embodied carbon assesment resulting from the harvestiging and rebuilt of a 100 m2 half-stone brick wall

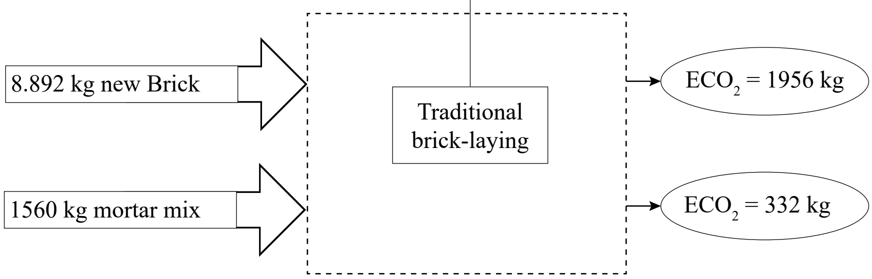
A. Harvesting



B. Processing



C. Assembly of 100 m² wall



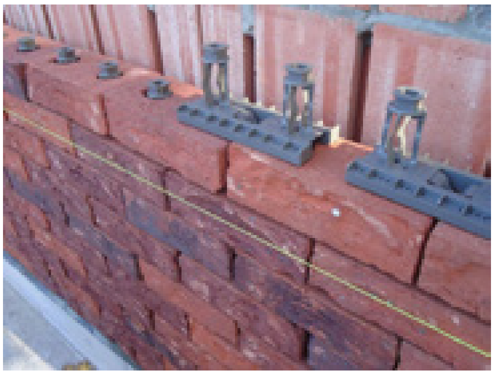
Summary

Demolition and re-assembly of 100 m² single layer waalformaat brick wall

Reduced brick waste = 5.928 kg

ECO_2 of extra required material = 2.288 kg

APPENDIX D - Visual overview of dry brick connection systems

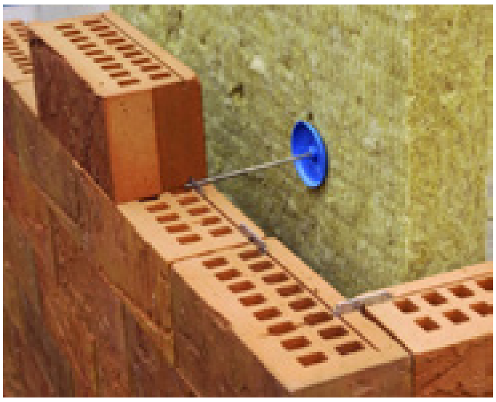


Facadeclick

Image retrieved from: https://www.colruytgroup.com/wps/portal/cg/nl/home/verhalen/circulair-bouwen (28.05.2020)

Fixbrick

Image retrieved from: https://www.verheijdenarchitecten.nl/kopie-van-01-groeneveld-1 (28.05.2020)



Clickbrick

Image retrieved from: http://wiki.bk.tudelft.nl/bk-wiki/Clickbrick (28.05.2020)

Drystack

Image retrieved from: https://drystack.nl/ (28.05.2020)

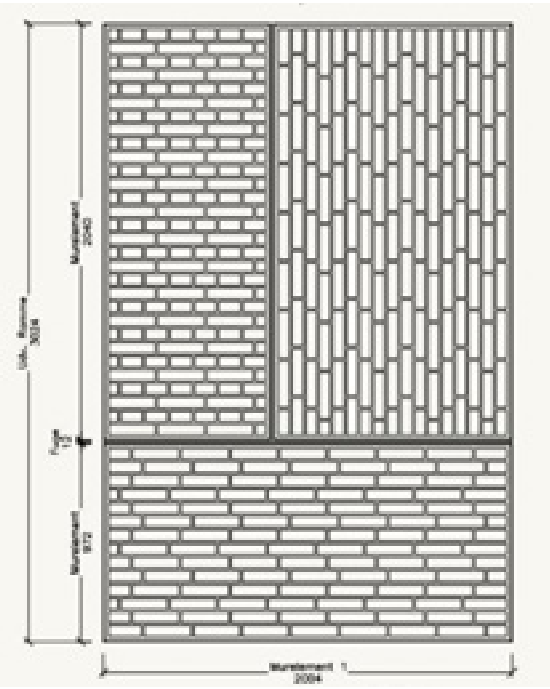
LeeBrick

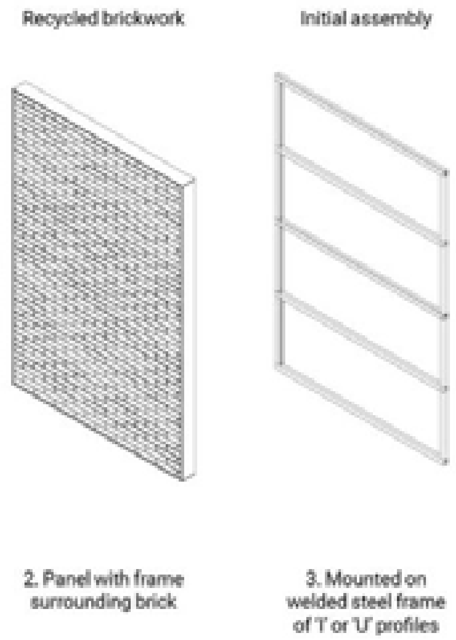
Retrieved from: http://leebo.nl/product/leebrick/leebrick-product-2/ (28.05.2020)

APPENDIX D - Weight estimation steel frame for cutting panel technique

Estimation of dimensions and weight of the steel frame
that can be applied on the cutting panel technique.

Concept and dimensions (Lendager Group, 2018)





Weight estimation + embodied CO_2 of the steel frames required for 100 m2 wall.

> 100 m^2 wall, with 6 m^2 panels = 100 / 6 = 17 panels

> Total length required steel profiles for one panel = 16 meter

> Assuming a U profile (50 x 50 x 5mm), weighing 5,44 kg/m . (https://www.smitstaal.nl/Koudgewalst_gelijkzijdig_U-profiel)

*> 16 meter steel u profile * 5,44 kg/m = 87,04 kg*

*> For 17 panels, the total weight of the steel frames = 87,04 kg * 17 = 1479 kg.*

> Embodied Carbon steel = 1,77 kgCO2/kg (Hammond and Jones, 2011)

*> Total embodied carbon = 1479 kg * 1,77 kgCO2/kg = 2618 kg CO_2*