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CASE STUDY

Assessment of the energy savings and CO_2 emissions reduction of glass structures through alternative demolition scenarios

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Abstract Glass is a material that has been significantly increasing its role in architecture in recent decades. Although glass is a material that can survive long, as can be seen from the archaeological pieces in many museums, in practice the glass structures that built nowadays have a finite life time. A notorious case is the original New York Apple Cube, which was removed and replaced within several years of original completion. Whatever the eventual lifetime of the structure, there will be a point where the structure needs to be demolished. This introduces critical questions about the relation between ecological impact and the demolition methods and procedure. This paper looks at the eco-impact of different end of life scenarios of glass structures, using the Haarlem glass cube as a well-documented example to determine the differences between various ends of life scenarios.

Keywords Glass construction · Laminated glass · End of life · Demolition method · Separation/collection method

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1 Introduction

The mass of produced glass increases every year. Where 40 years ago the bulk of the glass in buildings was simple flat glass, demands for improved comfort and reduced heating mean almost all glass placed in modern buildings is in insulated glass units composed of glass, metal, plastics and adhesive. Where safety requires it, laminated glass composed of glass panes laminated together with a polymer is used.

Although buildings are designed for a long life time, facades for office buildings are typically designed for a much shorter life façade than the life of the building by the façade industry. This increases the mass of waste glass. Within EU Framework Directive (2008/98/EC), cullet of flat glass is generally considered as waste and must be treated with varying interpretations across Member States. Cullet (broken or crushed for remelting) is very important for the new flat glass manufacturing, due to its contribution to decreas*ing* remelting energy and *reducing* the use of raw materials. In addition, depending on the obtained reduction of energy, it reduces CO_2 emissions during manufacturing. Recycling of glass waste coming from building demolition used to be simple, removing the float glass windows and re-melting them. Nowadays it is much more complicated. As ever more buildings are demolished, strategies to deal with the glass recycling are *becoming* necessary.

This paper looks at the problem of demolishing existing buildings and compares reusing the glass with recycling of the glass. In addition, it emphasizes that choosing the correct demolition method for existing buildings, is very important to increase the mass of glass recycled/re-used and thus to decrease the environmental effects of waste glass.

2 Problem analysis

Every human activity has many impacts on nature and these impacts cause damage to the environment. One of these activities is the construction of buildings. Every material used for building requires energy at the manufacturing phase and causes CO_2 emissions. The finiteness of many resources makes it necessary to think about how to save them by developing resource-saving methods in the global building industry. To successfully recycle and re-use the used materials in the buildings, it is necessary to think about re-use and recycling at both the architectural stage design stage and at the demolition stage.

Many architects focus only on the design of buildings *and forget* that there are other important aspects such as construction and demolition methods for sustainable architecture. Buildings consume significant mass of raw materials, and produce large mass of waste, thus the Construction and Demolition waste (C&D) from the global building industry is the single largest industrial waste flow in the world. The construction industry demands 40 % of the total energy produced in Europe, and generates 40 % of all waste produced (CIB 1999).

According to the European Commission, the total volume of C&D waste generated in Europe alone in 2012 was around 890 billion kg in Europe (European Commission 2012). The waste generated by construction in the European Union, is estimated at approximately 180 billion kg per year and approximately 75 % of the construction and demolition waste go to landfill sites and are thus not currently recycled or re-used. (Vefago and Avellaneda 2013).

To reduce the mass of waste materials and the energy required, it is necessary to think about waste management strategies, followed by re-use and recycling. Landfilling of waste should be the last option (Demirbaş 2011; U.S.EPA 2011; Vossberg et al. 2014). This hierarchy is a key tool to support decision making in waste management (Vossberg et al. 2014). So, an effective way to decrease waste volumes is the re-use of used materials and components after by carefully dismantling them in the demolition phase of buildings.

Reusing waste materials and components from buildings, *means using* this material again after prior usage. This method includes either conventional re-use where they are used again for the same function or creative re-use where they are used for a different function in other buildings. With this waste management method, energy savings and emissions reductions are maximized.

Recycling of waste materials from buildings, is to pass through at least one chemical transformation or to change their physical state. They don't need to serve in the same function as in their previous life cycle (Vefago and Avellaneda 2013). Recycling of wastes, is very important in order to reduce landfill space, energy consumption, raw material consumption and depletion of finite resources as well as the environment in general. Non-recyclable waste will require considerable additional landfill space, energy and *will increase* the overall cost.

With recycling of the C&D wastes, there are many problems such as contaminants. However, construction waste originating from more recent buildings is usually significantly less mixed and thus much less contaminated. Its recovery potential is as a result much higher than general demolition waste, which is much more mixed and contaminated. The share of waste from new construction is generally low compared to the total quantities of C&D waste (approximately 16 % in Finland). On the other hand, the waste of demolition and renovation processes, which is the bulk of C&D waste, tends to be significantly more contaminated and mixed. It is thus much more difficult and energy and capital consuming to recover and separate (European Commission 2011). Total recycling and reusing volumes without contaminants, of course, also depend upon the demolition, collecting and sorting system. Dismantling costs can be reduced from the start by properly allowing for this problem in the building project design.

Some 0.66 % of the C&D of buildings is flat glass waste. According to *the* European Commission 2003, each year, approximately 1.2 billion kg of glass waste are generated by construction and demolition of buildings (European Commission 2003). When flat glass waste from this source, is not properly sorted and mixed with other demolition waste, it will become chemically contaminated and cannot be used as cullet for new float glass production, without considerable further process-

Table 1 Costs of producing a 4 × 2m IG panel, 2 × 6mm FT and 10 mm coated FT, euros as provided by IFS glass for project "de wall" in Eindhoven, (prices are based on April 2014 price levels)

Cost component	Chinese supplier	% of total	European supplier	% of total
2 × 6 mm plate 4 × 2 m	48 × 2	6,09	98 × 2	8,35
10 mm coated annealed	320	20,3	560	23,87
Grinding 6 mm	32 × 2	4,06	40 × 2	3,41
Grinding 10 mm	56	3,55	80	3,41
Tempering	3 × 80	15,22	3 × 160	20,46
Laminating 6 mm	240	15,22	400	17,05
Producing IG panel	160	10,15	450	19,18
Shipment taxes etc.	400	25,38	100	4,26
Total	1576	100	2346	100
Cost 8 m^2 cavity insulated brick wall	1760			

ing such as washing, cleaning with organic solvents and rewashing. This contaminated waste glass thus requires significant cleaning and processing before it can meet the high quality criteria set by the float glass industry for post-consumer cullet.

Not sorting and separating flat glass waste material at the demolition site thus significantly affects the quality of new glass products. Contamination from sources such as aluminium, polymers from laminated glass, adhesives, insulating glass unit spacers etc. contaminate the glass melt and can cause bubbles, ream knots and colour variations of the newly produced glass. These contaminations significantly affect the float glass manufacturing process, which due to the high and stringent quality demands is sensitive to even very low levels of contamination. Additionally, the quality requirements for float glass manufacturing are significantly higher than in other glass sectors (such as container and non-optical fibre glass).

In addition, although the use of cullet is of major importance for the glass industry, cullet ratio ranges from 10 to 40 % for a float furnace. So, to decrease the energy requirements and emissions for the environment, increasing the re-use of flat glass in new building construction taking account of the quality and size of glass elements is essential.

In the United States, at least 25 % of all flat glass is laminated glass and laminated glass is the single fastest growing segment in the glass industry being used in different areas such as architecture, automotive, solar panels, solar concentrator mirror manufacturing and transparent armour production. This creates a vast energy requirement. Laminated glass manufacture, requires energy for many processes in the manufacturing chain. Heat is required to melt a batch, transform the molten glass into flat sheets, to bend the glass into shape, edge grind the edges, clean and dry the glass, de-air and autoclave the laminate to finally produce the clear window, which is required by the end-consumer. All this cumulative energy consumption is stored in the final products. (Allan et al. 2011). A cost breakdown for a modern 4 × 2 m insulated glass panel composed of a laminated 6.6.2 fully tempered pane and a coated 10 mm fully tempered pane are given in Table 1. The data were supplied by IFS glass and come from the "wall project in Eindhoven which was constructed in 2015.

Basically this shows that only some 25 % of the cost is in the float glass. It also shows that these panels are quite price competitive with traditional building materials such as masonry. Recycling this panel back to new float glass thus destroys 75 % of the investment in the panel. This will later be more precisely analysed in energy terms.

So, insofar as reusing waste laminated glass products is from both a financial and an eco-design perspective much more preferable, providing significant energy and emission savings compared to the conventional recycling of laminated glass, because the stored grinding, tempering and laminating energy is not thrown away.

Reusing of glass can have many problems which should be considered before demolition. These are quality control of re-used glass and gas losses in Insulated Glazing Units. In such a case, used glass can be sent to the recycle area or re-used in available buildings or refurbished by refilling the gas. Glass is one of the most durable materials. Modern glazing also can technically be very durable, especially if the double or triple glazing components would be designed for easy refurbishment, e.g. replacement of the gas in the insulation glazing units. In addition, when laminated glass is re-used, it requires dimensional compliance and harmony of thickness with the requirements of the new building. Although it seems difficult, it is not impossible, but requires good planning before demolition and good transportation and storage. And, after dismantling of components, they can be offered on an open market for re-use after refurbishment in a new project at a considerable savings in cost and ecological impact. In the longer term sizes of glass components could be standardized in some ways to make re-use easier although it is expected that the financial incentive of re-using glass components should create a big enough market. In other words, the lowest cost and eco-impact requires careful attention to component and structure design with proper detailing to allow for easy refurbishment and re-use.

As well as properly designing the demolition process by properly considering building design, it is important which methods should be used for demolition and collection to effectively recycle/re-use the glass in buildings destined for demolition. There are many possible demolition methods, such as using explosives, wrecking balls, hydraulic crushers and pulverisers, and manual dismantling. The selection of the demolition method that will be used is dependent on the project conditions, construction type, work force, time and site constraints and the availability of equipment (Coelho and Brito 2011; Guy 2003; CTIC 1995; CIB 2005; Shultmann 2005). But, the selection of the demolition method also greatly affects both the mass and the quality of glass that can be recycled or re-used and the overall cost of the whole operation (Coelho and Brito 2011). For instance, explosives or hydraulic crushers and pulverisers are often employed because these methods significantly save on time and labour (Wu et al. 2014). But, these methods not only significantly reduce the quality of glass recyclables, but also the quantity.

In the literature there are two well-known collection methods: source-separation and commingled:

Source separation—materials are separated on site, usually into a specially designed truck or container with different compartments for different materials.

Commingled- materials are mixed together in a lorry, which compacts the materials. The fragmented recyclables are separated later, usually at a materials recycling facility (MRF) (Apotheker 1990).

Source separation of C&D waste, causes considerably less contamination of recyclables, especially contamination sensitive glass waste, and thus allows recycling or re-use of a much higher proportion of the total glass waste. While source separation methods increase the value and thus the revenue from saleable materials, it decreases overall cost and produces more local jobs. But commingled collection mixes the materials and the concomitant very high risk of contamination makes recycling of some materials, especially glass, costly and uneconomical. For glass waste, the commingled collection method requires additional treatments and further processing to prepare the contaminated glass waste for the cullet stage and also significantly decreases the quality of the resulting glass product. While collected material can be recycled after commingled collection, typically 12–15 per cent is wasted in English MRFs (Dougherty Group LLC for WRAP 2006), which compares to less than 1 % for source separated systems (Friends of Earth 2009).

There is thus a need for a clear waste management hierarchy, which defines a set order of preference for different waste management strategies, preferring source separation because it leads to high levels of re-use and recycling (U.S. EPA 2014).

Re-use of refurbished glass components requires significantly less energy in order to make the components suitable for its new functions with equal performance compared to all new production. A relatively small mass of energy is required to refurbish these components in order to comply with the current building standards, which also generates a minimum of waste (Vefago and Avellaneda 2013). Re-use of parts of a to be demolished building, should always be considered as part of the demolition planning process. Dismantling methods will be much more successful for a re-use scenario than excavator or blasting methods of demolition. To produce glass panels that meet the strict requirements of modern buildings, the raw materials and fossil energy used must be of a high quality and purity. But, re-used glass elements can be rededicated to a new use without the concomitant loss of extra energy and raw material for production inherent to recycling of the material.

There are many reasons to recycle glass. Some of them are the limited supplies of finite raw materials and environmental pollution due to the high material and energy costs. Recycling of demolition waste should always be considered as another part of the demolition planning process after preparing suitable elements for re-use. For the glass industry, recycling provides a considerable cost, energy and emission saving especially for the batch processing of glass. According to IEA; increasing the use of cullet (waste glass pieces) by 10 % in the melting mass decreases the energy consumption of melting by about 2–3 % (IEA 2007). And for recycling of glass and other materials, dismantling and source separation methods will be more successful than the excavator method whose commingled collection results in the presence of contaminants.

So within this context, with the aim of emphasizing the evident benefit obtained from source separation and reusing of glass waste, three demolition methods and two collection methods were selected and analysed for the Glass Cube in Raaks Square, Haarlem in the Netherlands. Complete drawings and specifications for this project were available, making it thus suitable for a complete analysis. This to compare their relative effectiveness, determining the individual advantages and disadvantages by analysing the different potential savings in energy and CO_2 emissions. To this end, the results were compared according to achievable reductions of energy and CO_2 emissions, minimising glass waste, maximising the mass of recyclable/reusable material/components.

3 Case study

The Glass Cube in Haarlem's Raaks Square, was built in 2011 and is shown in Fig. 1. It is a typical modern glass/steel hybrid structure. On a square in the historic city centre of Haarlem in the Netherlands on top of an underground car park a fully glass entrance building was designed by architect Kraayvanger Urbis. The structural design was done by ABT. Normally it would be expected to have a lifetime of about twenty years. The dimensions of the Haarlem Glass Cube are 7.05 × 7.05 × 7.05 meter. The design uses the following glass elements: four glass walls forming the facades composed each of 9 glass panels of 2.35 × 2.35 square meter and the glass roof also made from 9 glass panels of 2.35 × 2.35 meter. The glass panels in the roof exists of 2 heat strengthened (HS) glass panels with each a nominal glass thickness of 12 mm laminated by 2 PVB-foils (total glass 1212.2 HS). The glass panels

Fig. 1 Glass Cube in Haarlem's Raaks Square, built in 2011 and designed by Kraayvanger Urbis

in the facades are formed of laminated heat strengthened glass with a glass composition of 108.2 mm. The glass walls of the facades are strengthened in order to take up the wind load and to take up the loads out of the roof structure by 2 vertical glass fins of 7-meter-long and 4,5-meter width in each glass wall. The glass fins are also made out of laminated tempered glass with a glass composition of 121212.2 HS. The majority of the materials used in the Glass Cube is laminated glass, as is shown in Table 2. The total mass of laminated glass was calculated as 14,065 kg *based on the nominal thicknesses*. But, it should be kept in mind that the mass of the structure is slightly over-estimated because the real thickness will be smaller due to production tolerances.

The weight of glass was calculated with the way to calculate the weight of glass is 2.5 kg per millimeter per square meter. So, weight of glass was calculated by using Eq. 1. It is based on nominal thickness as the actual thicknesses are not available.

$$W = a \times \mathrm{b} \times \mathrm{t} \times 2,5 \quad (1)$$

where W kg is the weight of glass, a and b is each dimension of the edges, t is nominal thickness of glass.

Table 2 Materials used for Glass Cube

Component	Material	Unit	Mass
Wall /Roof	Laminated Glass	kg	8,946 / 2,907
Fin	Laminated Glass	kg	2,211
Total	Laminated Glass	kg	14,065

3.1 Study objectives and methodology

In this study, a survey was conducted with the following objectives:

(1) To compare the savings for glass resulting from commingled or source separation of glass construction in building demolition.
(2) To analyse three demolition alternatives by using dismantling and excavator methods in the end of life demolition phase of the Glass Cube.
(3) To determine the mass of glass waste only resulting from commingled collection and source separation.
(4) To determine the energy savings and CO_2 emission reduction of re-use and recycling of laminated glass waste according to the three demolition methods.
(5) To evaluate the relative performance of the three demolition methods investigated in terms of energy saving and CO_2 emission from glass cycling, mass of recycled and re-used material.

For this the following scenarios were assumed and analysed: (For detailed information about scenarios, please see Sect. 3.2)

Ag Careful removal of glass components, refurbishment and re-use in another building. This scenario is theoretical as the building industry is not currently setup for this. It is assumed that re-used glass components are re-used in another.

Bg On-site source separation during demolition with maximum recycling of glass components into new float glass.

Cg Demolition with commingled collection. Recycling of glass waste into new float glass where possible

The CO_2 reduction and energy saving resulting from reusing and recycling was calculated using the laminated glass data in the (Granta CES EduPack 2015) database. The energy saving and CO_2 reduction data consists only of the processing and grinding energy of laminated glass. This does not include the effects of local/consumer energy and emissions for transportation required for recycling and separation. It is assumed that the life cycle of glass was cradle to gate and savings are only obtained from the laminated glass obtained from demolition of Glass Cube using dismantling and demolition with excavator. The energy savings and emission reductions for the glass waste were calculated for scenario Ag by using Eq. (2) and for the Bg and Cg scenarios were calculated using Eq. (3).

$$\Sigma S = (\text{Mrc} \times \text{saving from recycling of glass}) + (\text{Mru saving fom reusing of glass}) \quad (2)$$

$$\Sigma S = (\text{Mrc} \times \text{saving from recycling of glass}) \quad (3)$$

where ΣS MJ/kg is the sum of savings from the related scenario, Mrc is mass of recycling waste glass and Mru is mass of reusing waste glass as kg. The savings from recycling/reusing glass are given in Tables 5 and 6 as the savings in MJ from 1 kg waste glass being recycled and/or re-used.

3.2 Flow diagrams, scenarios and demolition/collection methods

In this case study, for the whole building, it was suggested that there are three alternative flow processes to demolish the Glass Cube. In these flow processes, first (A) consisted of a dismantling/ripping method as a demolition method in context of reusing and recycling of waste materials, and source separation as a separation method by using separate conveyors for each material type. According to flow diagram A; it was assumed that most of the glass (90 %) waste was re-used by transporting it to a re-use area and the remaining glass pieces were dismantled and transported to the recycle area for the glass recycling. Because of choosing a 90 % glass recovery ratio it is assumed that most of the glass can be re-used in new buildings after demolition if the planning is done properly. The savings of resources from the recycling of rubber, sealants, coatings, *laminating foils such as PVB* and steel were ignored and focused only the savings from laminated glass. It was assumed

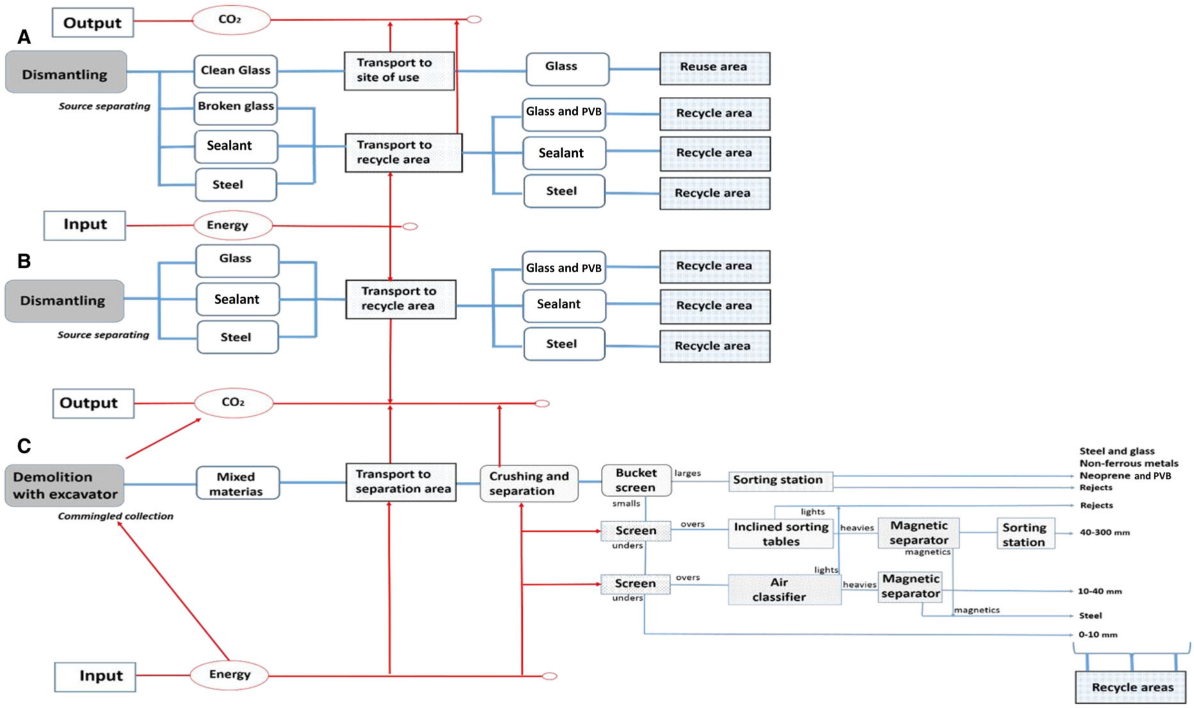

Fig. 2 The scheme for assumed demolition/separation flow diagrams and ways that can get materials in Glass Cube in Haarlem. Alternative A is for dismantling, source separation, and glass reusing. Alternative B is for dismantling, source separation, and glass recycling. Alternative C is for demolition for excavator, commingled, off site separation, and glass recycling. Coatings were ignored. (Third diagram (MRF system) is adjusted from Ravensburg, Germany C&D recycling facility, Stein 1993) This scheme only shows ways that can get materials, not means to calculate energy and CO2 emissıons resources from transporting of materials to recycle and re-use area. For calculated savings, see Fig. 3

that *removed sealants and residual* pieces of steel are sent to their own recycling areas.

The second flow diagram (B) consisted of a dismantling/ripping method for demolition stage of Glass Cube in the context of recycling all used materials with source separation method by using separate conveyors for each material type. According to flow diagram B; it is assumed that approximately all of the glass wastes (99.5 %), sealants and stainless steel waste was recycled by transport to their own recycle areas. 0.5 % glass loss was assumed, because of unexpected problems during demolition, ripping and collection phase. But this loss is a very small part of the total mass of glass. Also the loss of resources due to transportation was ignored.

The last alternative (C) consists of using an excavator for demolition and commingled collection for demolition stage of Glass Cube and residues were moved out to separation area to recycle in mixed type (see Fig. 2). According to flow diagram C; it was assumed that most of the glass wastes (86.5 %), sealants and stainless steel waste were transported to separation area to separate mixed materials and then each of them were transported to different recycle areas in separately transportation. (For reasons of glass rate selection, see Sect. 3.3. as loss rates). The savings and missing resources from transporting to the recycling area, separation of mixed materials and recycling of sealants, coatings, PVBs and pieces of steel were ignored.

The main object in this study, as the main material of the Glass Cube is glass, with the aim of detecting savings from glass wastes more clearly, it was determined that the cycles of glass waste and flow process of glass waste should be examined separate from the main flow diagrams as can be seen in Fig. 3. The glass cycle scenario was determined as follows: in the first flow diagram (A), glass is re-used 90 % and transported to the re-using site and glass broken during the ripping is recycled using source separation. In the second flow diagram (B), all of the glass is recycled and transported

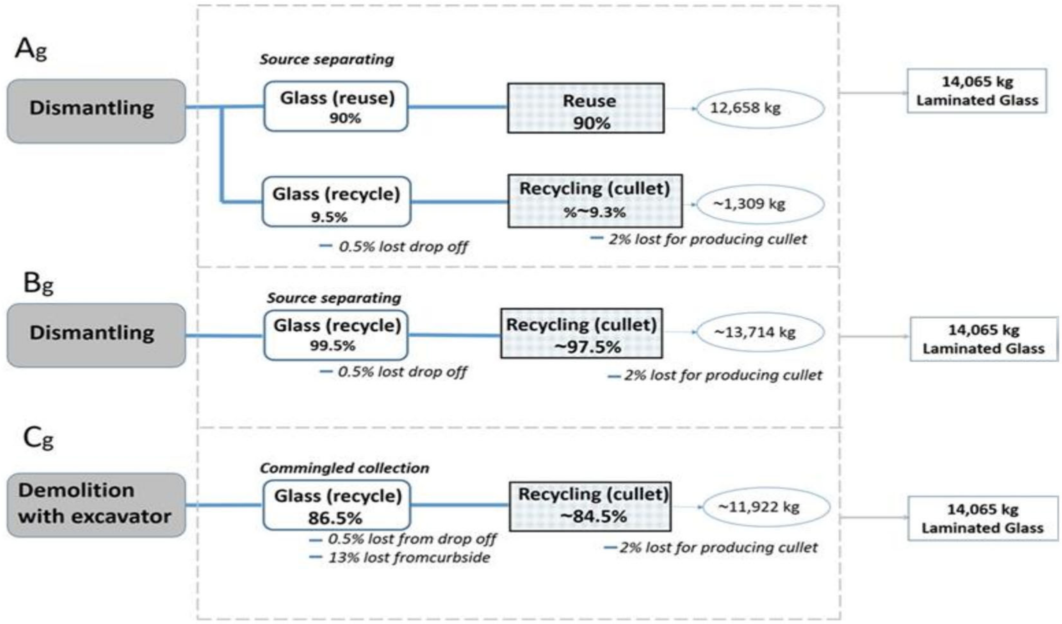

Fig. 3 Laminated glass cycle flow diagrams for Glass Cube in Haarlem. Scenario Ag is for mostly reusing and recycling of the laminated glass with source separation. Scenario Bg is for recycling of the laminated glass with source separation. Scenario Cg is for recycling of the laminated glass with commingled collection. All the calculations for savings are only based on laminated glass

Table 3 Suggested separation methods and cycle type according to glass cycle scenario for Glass Cube
*** Means, mostly applied, * Means, minimally applied, – Means, not applied

Scenario	Separation method		Cycle type	
	Source separation	Commingled	Recycle	Re-use
Ag	***	–	*	***
Bg	***	–	***	–
Cg	–	***	***	–

to the recycle area. And in the last diagram (C), glass is transported to the separation area so that glass is separated from other materials (the sealant and steel). And these flow diagrams were designated as Ag, Bg and Cg according to the different scenarios (for the sum up, see Table 3).

3.3 Loss rates

On the basis of loss rates observed elsewhere, which indicate the mass of material lost between collection and processing, losses of 13 % in the glass tonnage from commingled collections, 0.5 % in the tonnage from drop-offs and business, and 2 % in cullet preparation were assumed in the glass recycling scenario (Vossberg et al. 2014; Edwards and Schelling 1999; European Commission 2006; U.S.EPA 2011). These loss rates were used in order to determine the mass of recycled and re-used glass in this study (also see Fig. 3). The loss rates for this case study are given in Table 4. The Cg scenario has the highest loss rate due to the commingled collection while scenario Ag has the lowest loss rate as it re-uses most of the glass waste and uses source separation.

3.4 Energy savings and reduction of CO_2 emissions due to glass reusing/recycling

Glass making is a very energy intensive process. In general, the energy required for melting glass accounts

Table 4 Loss mass of glass waste and mass of recycle/re-use of glass according to glass cycle scenario

Scenario	Loss type/kg glass			Cycle type		
	Drop-offs	Commingled	Cullet prep.	Recycle	Re-use	Total
Ag	70.32	–	26.72	1,309.96	12658	14065
Bg	70.32	–	279.89	13,714.79	–	14065
Cg	70.32	1,828.45	243.321	1,922.91	–	14065

for over 75 % of the total energy requirements of glass manufacture. The specific energy demands for glass production also depend on the type of end product (i.e. chemical composition), the percentage of cullet in the feed, the efficiency of the processes, and the type of furnace (EEBPP 2000). Since the flat glass production sector is a very diverse sector containing both modern energy efficient and old and relatively inefficient production plants, a single value for energy consumption is difficult to determine. According to the IPCC and the European Commission the specific energy demand for flat glass is 5.5–8 MJ/kg (European Commission 2008). Another assessment by Beerkens et al. (2004) reports the energy intensity for basic float glass as being 5.3–8.3 MJ/kg per production. This is very dependent on the size and technology of the furnace and the proportion of cullet used. GLS-BREF (2013) reports the average value of 7.5 MJ/kg of production within the EU-27. Schmitz et al. (2011) assessed the energy consumption and CO_2 emissions of European flat glass industries and arrived at an average energy intensity of around 9.2 MJ per kg of saleable output. The corresponding figure in the US is significantly higher at around 10.7 MJ/kg of output. These data were for the year 2002 (Worell et al. 2008). According to the (Granta CES EduPack 2015) database, the embodied energy of float glass is given as 10.1–11.1 MJ/kg glass for flat glass. In addition, 7.82–9.46 MJ/kg is given for glass molding and 25.6–28.3 for grinding.

Laminated glass production requires even more energy rather than simple float glass. As well the base energy required for primary glass production, additional energy is required for the edge grinding processes which are necessary if the glass is to be tempered or aesthetically if the edges are exposed, production of the laminating foil and the laminating process. These extra steps require additional energy and also cause additional CO_2 emissions. According to the Granta CES EduPack (2015) database, the embodied energy of laminated glass is given as 27.7–30.6 MJ/kg. A lot of this energy goes into the production of the grinding heads and the laminating foil, some energy being used to work the grinding machines and to work the autoclaves. The data shows that laminated glass production is an energy intensive process. For laminated glass production the CO_2 footprint is given as 1.67–1.84 kg CO_2/kg for primary production, 0.494–0.546 kg CO_2/kg for molding of glass and as 2.35–2.6 kg CO_2/kg laminated glass for grinding.

In this study, the specific energy demand of laminated glass is given in the Granta CES EduPack (2015) as 27.7 MJ/kg laminated glass, the molding glass energy is as 6.18 MJ/kg and the grinding process energy is as 31.3 MJ/kg of laminated glass. Thus reusing 1 kg of laminated glass saves 65.18 MJ/kg of energy, the CO_2 emission saving will be 4.514 kg CO_2/kg of laminated glass (see Table 5). These values were used for calculating the energy savings in scenario Ag. Because there will be no additional production and grinding processes if the laminated glass components are reused for the same function in another building. Consumer transport and local transport for collecting and transporting laminated glass to the new site of use for reusing are not included by calculating energy savings. The cycle of glass was assumed as cradle to gate. The savings were calculated using Eq. (2) in Sect. 3.1.

Cullet (broken or crushed glass for re-melting) is of very high importance for the float glass manufacturing industry, because of its direct contribution to energy and raw materials saving and reduction of CO_2 emissions from the glass melting process while reducing the mass of waste material going to landfill. Cullet thus helps to meet manufacturer commitments to climate change policy and in particular on carbon trading in the framework of the EU Emission Trading Scheme (Ecofys 2009; Glass for Europe 2010). Increasing the use of cullet by 10 % in the melting mass decreases energy consumption by about 2–3 % (IEA 2007). It has been

Table 5 Used unit energy savings from recycling and reusing of 1 kg waste laminated glass according to scenarios

Energy savings (MJ/kg glass)				
Scenario total	Primary prod.	Glass molding	Grinding	Process
Re-use/Ag	27.7	6.18	31.03	65.18
Recycle/ Bg-Cg	6.3	–	–	6.3

Table 6 Used unit energy savings from recycling and reusing of 1 kg waste laminated glass according to scenarios

CO_2 Emission saving (kg/kg glass)				
Scenario	Primary prod.	Glass molding	Grinding	Process total
Re-use/Ag	1.67	0.494	2.35	4.514
Recycle/ Bg-Cg	1.02	–	–	1.02

proven that a reduction of 3.3 % in specific energy consumption is the result of each additional 10 % increase in cullet (Fleischmann 1997; Worell et al. 2008). For each additional percent of cullet added there are estimated energy savings equivalent of 8.1 MJ/kg of glass in a 1993 survey of furnaces in German-speaking countries in Europe.

When, 1000 kg of glass is produced only from cullet, no reaction energy is required for the batch (155 kWh), less water must be vaporized (18 kWh) and no process gasses would be produced (170 kWh). So, when the energy saving is calculated in this study, an energy saving of 343 Kwh (1.234 GJ) would accrue for 1000 kg of glass produced solely from cullet instead of virgin raw materials (Carbon Trust 2004). But, for the laminated glass, this saving is significantly greater than for float glass. According to Granta CES EduPack (2015), the embodied energy with recycling for laminated glass is given as 21.4–23.7 MJ/kg and the CO_2 footprint is 0.649–0.718 CO_2kg/kg-laminated glass. So, when 1 kg of laminated glass is recycled, the energy saving can be estimated as 6.3–6.9 MJ/kg glass and 1.02–1.12 kg CO_2/kg glass (see Table 6). Technically it is not feasible to produce flat/laminated glass solely using cullet. Flat/laminated glass is generally produced with a certain percentage of recycled glass that is currently in the range of 20–40 %. So, data of energy saving with the recycling was accepted as 6.3 MJ/kg and when 1 kg cullet was used in laminated glass manufacturing, mass of avoided CO_2 emission was as 1.02 kg CO_2/kg glass for glass scenarios Bg and Cg. Consumer transport and local transport for collecting and transporting laminated glass to separating area (for Cg) and recycle area (Bg, Cg) are not included by calculating energy savings. The savings were calculated using Eq. (3) in Sect. 3.1. The saving data that used for calculating of saving from reusing/recycling of 1 kg-laminated glass are listed in Tables 5 and 6.

3.5 Results of study

The energy savings and CO_2 emission reductions obtainable by reusing and recycling laminated glass, calculated by the procedure described in Sect. 3.1, are illustrated in Fig. 3. They are shown as absolute values of the energies utilized in the primary production, grinding, processing and laminating of laminated glass with at the end of life either re-use or recycling according to the different scenarios. The savings for scenario Ag were calculated using Eq. (2), and for scenarios Bg and Cg using Eq. (3). The results clearly show that the most significant energy savings and emission reductions are achieved by reusing laminated glass. This is because the embodied energy and emission involved in the additional processing and grinding and lamination is retained as is seen in Figs. 4 and 5. The energy saving and CO_2 emission reduction that is obtainable by reusing laminated glass (Ag) is roughly ten times and five times that which is obtainable by recycling the laminated glass using scenarios Bg and Cg respectively.

Additionally, the energy savings and emission reductions calculated using a source separation scenario (Ag, Bg) are better than for the commingled collection scenario (Cg). This is because the mass of recyclable material is significantly higher when source separation is used than for the commingled collection scenario. The difference is approximately 13 %. Local and consumer

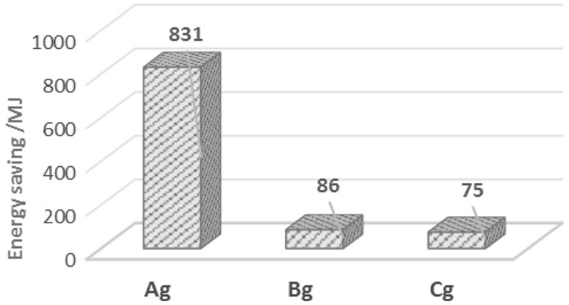

Fig. 4 Total energy savings according to the three different scenarios for the Haarlem Glass Cube

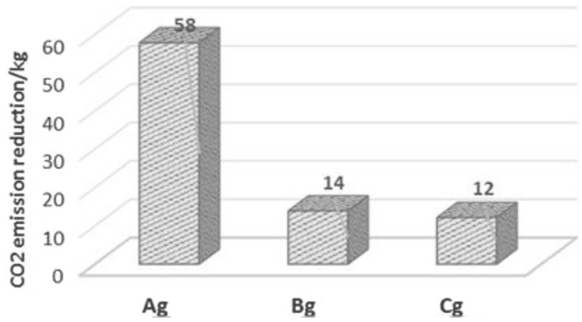

Fig. 5 CO_2 emission savings according to three different scenarios for the Haarlem Glass Cube

transport for collecting and transporting laminated glass for reusing/recycling are not included in these as these are assumed to be comparable for all scenarios.

4 Discussion

The different demolition and separation scenarios investigated for the end of life scenario for the Haarlem Glass Cube result in significantly different reductions of energy consumption, CO_2 emission and the mass of recyclable material. When the different flow diagrams are examined, it is seen that the best result is obtained from flow diagram A and the second best result is obtained from flow diagram B. Careful dismantling of a glass building during demolition, is the prerequisite first key step towards achieving the highest possible rates of recycling/re-use. This method may increase the need for labour onsite and the time required for demolition. Because, it needs *time and* motion analysis of the actual demolition process and *a greater* labour force. But, this method significantly decreases the CO_2 emission and energy compared to the excavator method. In addition, a selective source separation method avoids the breakage of glass components making re-use and contaminants for better recycling possible.

In flow diagram C, the excavator method was chosen for demolition with the resulting commingled collection of all the materials that compose the Haarlem Glass Cube. With this method, it is impossible to separate the materials from each other at the source. So, mixed materials have to be separated in the complex separated area first and then have to be treated to remove impurities before recycling. Although the presented savings values don't include this missing part, in real life, it means that additional energy; emission and labour are required to achieve reasonable recycling rates while still reducing the quality of the recycled product by the unnecessary pollutants introduced by commingled collection.

As well as the savings of resources from laminated glass was calculated, the other materials which are used in Glass Cube were investigated using with cognitive observation in terms of saving energy and CO_2 reduction, and increasing the total mass of recyclable materials. As you can see in Fig. 2, we had proposed recycling of steel and sealants in the proposed demolition scenarios as end of life cycle. So, if we assess these materials, collected steel can be recycled and it is estimated that savings are higher in scenarios A and B. This is because in scenario C the steel will have more impurities and less will be collected than in scenarios A and B due to the excavator demolition and commingled collection. As you can see in Table 7, glass and steel were investigated in terms of saving energy and CO_2 reduction, and increasing the total mass of recyclable materials bearing in mind demolition flow diagrams and scenarios.

For flow diagram A;

– Waste laminated glass was assumed to be re-used in other buildings. So, according to calculations, the most significant energy saving, reductions and cycle mass are achieved by reusing laminated glass. So, energy saving, reduction of CO_2 emission and cycle mass was coded for glass as high (***) in Table 7. And, waste laminated glass will be used as previous cycle with reusing and dismantling method, although its quality may decrease. So, same usability as previous cycle was coded as high (***) while quality of product was coded as medium (**) in Table 7.

Table 7 Assessment of the suggested flow diagrams and materials used for Glass Cube according to environmental benefits

Flow diagrams	Energy saving	Reduction of CO_2 emission	Mass of cycle	Same usable as previous cycle	Quality of product	Reasons
A (for glass)	***	***	***	***	**	None of embodied energy and emission
						None of grinding energy and emission
						No lost because of source separation
						No lost from cullet preparation
						Will be used for the same function
						Can be lost own quality
A (for steel)	***	***	***	**	***	Embodied energy and emission is reduced (more energy saving with steel recycling)
						No lost because of source separation
						Can be used for the same function
						Can be produced in good quality in the absence of impurities
B(for glass)	**	**	**	**	***	Embodied energy and emission reduced
						Grinding energy and emission reduced
						Lost from cullet preparation
						Can be produced for the same function
						Can be produced in good quality because of not impurities
B(for steel)	***	***	***	***	***	(See reasons for A for steel)
C (for glass)	*	*	*	**	*	Less energy saving and less emission reduced due to loss of commingled coll.
						Less grinding energy saving and less emission reduced due to loss of commingled coll.
						Extra energy for separation and transport to separation area
						Energy of treatment for impurities
						Lost from cullet preparation and commingled collection
						Can be produced for the same function with treatment before recycling
						Must be applied a treatment for the quality product
C (for steel)	**	**	**	***	***	Less energy saving and less emission reduced due to loss of commingled coll.
						Lost from commingled collection
						Extra energy for separation and transport to separation area
						Can be produced for the same function with treatment before recycling
						Must be applied a treatment for the quality product

Note: * low, ** medium, *** high, KPI: Key performance indicator

– Waste steel was assumed to be recycled by transportation to its recycling area. In this study, we focused only the savings which can be obtained by reusing/recycling waste laminated glass. When waste steel was recycled, its functionality can change, but it can be used in the same function with good result. So, same usability as previous cycle was coded as medium (**) while quality of product was coded as high (***) in Table 7.

For flow diagram B;

- Waste laminated glass was assumed to be recycled by transporting it to its recycle area. Energy saving and reductions was calculated and determined energy savings and reductions data which resource from recycling of laminated glass. So, energy saving, reduction of CO_2 emission and cycle mass was coded for glass as medium (**) by taking into account data of reusing. Mass of recycling mass will decrease because of cullet preparation phase. But, cullet may be used in the production of float glass or can be sent to another recycling sector because of lack of quality. The new glass can be produced in good quality in the absence of contaminant. So, mass of recycling mass was coded medium (**) by comparing flow diagram A. And, same usability as previous cycle was coded as medium (**) while quality of product was coded as high (***) in Table 7.
- Description of waste of steel for flow diagram B is the same as flow diagram A.

For flow diagram C;

- With recycling of waste glass by using commingled collection, less energy savings and less reductions were determined because of loss of cullet preparation and commingled collection. In addition, it requires that extra energy for separation, treatment for impurities and transport to separation area. So, energy saving and reduction of CO_2 emission was coded for glass as low (*) by comparing other flow diagrams (A and B). Recycle mass will decrease because of cullet preparation phase. So, mass of recycling mass was coded medium (**) by comparing flow diagram A. The cullet can be added to phase of float glass production for the same function with treatment, but for the good quality of new glass, a treatment must be applied. So, same usability as previous cycle was coded as low (**) while quality of product was coded as low (*) by comparing other flow diagrams (A and B) in Table 7.
- With the recycling of steel comes another energy savings and emission reduction but it requires extra energy for separation and transport to separation area. In addition, there is a loss due to commingled collection. So, energy saving and reduction of CO_2 emission and cycle mass was coded for glass as medium (**) by comparing other flow diagrams (A and B).

It can be seen easily that reusing laminated glass is a very effective method for its end of life in terms of energy saving and emission reduction. In addition, dismantling and source separation are mutually supportive demolition and separation methods. Reusing glass can have many problems which should be solved before planning of demolition. Glass is one of the most durable materials. Modern glazing also can technically be very durable, especially if the double or triple glazing components would be designed for easy refurbishment, e.g. replacement of the gas in insulated glazing units. In addition, when laminated glass is reused, it requires dimensional compliance and harmony of thickness with the requirements of new building. Although it seems difficult it is not impossible, but it only requires good planning before demolition and good transportation. And, after dismantling of components, they can be offered on an open market for re-use after refurbishment in a new project at considerable savings in cost and ecological impact. In the longer term sizes of glass components could be standardized in some ways to make re-use easier although it is expected that the financial incentive of re-using glass components should create a big enough market. In other words, lowest cost and eco-impact requires attention to design detailing to allow for refurbishment and re-use.

5 Conclusions

In this study the effect of different demolition and collection methods on the mass of obtained recyclable material and the reductions in energy consumed and CO_2 emission is studied for the demolition of a laminated glass building. The Haarlem Glass Cube being used as an example for this case study. In addition to determining the possible mass of recyclable materials, the differences between a re-use and recycle scenario were analysed. Within this context, the energy and CO_2 emission reduction were calculated according to two different demolition/collection scenarios for the Haarlem Glass Cube. The results clearly show that a tenfold savings with respect to energy and a fourfold savings with respect to CO_2 emission are obtained if the laminated glass is re-used after a source separation method. The industry currently does not provide for this. It should however be noted that the car industry and domestic appliances industry have a legal obligation to take back and re-use/recycle their products. The introduction of a similar scheme to glazing or facades would effectively force re-use on the industry.

The energy savings resulting from source separation scenarios exceed those for the scenario with commingled collection. Additionally, when calculating the mass of energy that is used for additional glass treatment to remove the impurities of glass and the extra energy for the supplemental separating process is added, the energy cost and CO_2 emission of commingled collection will increase further. Careful dismantling of glass buildings during demolition, is thus the first and most critical step towards achieving the highest possible recycling/re-use rates and towards end of life energy and emission savings in the glass construction industry. Especially for laminated glass, because of the high-embodied process and grinding energy, the re-use of old glass components should be investigated to see if the properties after 20 years of use are still sufficient for a further 20 years after refurbishment. Currently no information about the technical possibilities of re-use exist. As the glazing industry has a clear financial incentive, as seen in Table 1, to produce new components, such a study is unlikely to come from the glazing industry. To achieve this, a proper dismantling method combined with good source separation is the essential first key step to obtain clear, unbroken elements and more glass for recycling. To achieve this, it is critical that glass components are not only designed for assembly, but also for disassembly, refurbishment and re-use.

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