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BIM Material Passport to Support Building Deconstruction and a Circular Economy

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Abstract

Advanced computational tools like building information modeling (BIM) have great potential for facilitating environmental life cycle evaluation of buildings, including their construction, to support circular material flows from new and end-of-life (EOL) buildings. Here we introduce a method and case study that combine BIM and material flow analysis (MFA) to define a material passport for a LEED-rated commercial building in Israel. The building was designed using "BIM in the big room", a product development technique in which designers of different sub-systems are brought together to promote communication, collaboration and short-cycle problem solving. Material passports use BIM to classify and quantify building objects by their material constituents to assess their potential for recycling at the building's demolition stage. The material passport can be combined with life cycle inventory data to evaluate the environmental impacts of the embodied material in the building and guide best practices for deconstruction. The BIM analysis shows a high mass of concrete (110, 000 ton) and glass curtain walls (27,000 m^2). The concrete can be recovered from the structural frame if dismantled. The glass curtain walls may also be recovered for reuse in other projects or recycled into new glass products.

Keywords

Building information modeling (BIM), Material passport, Life cycle assessment (LCA), construction and demolition waste (CDW), greenhouse gas (GHG).

1. Introduction

Rising populations in cities around the world are raising demand for continued infrastructure provision to meet housing needs, which incurs demand for natural resources. In addition, the construction industry is one of the most polluting industries in the world (EPA, 2009; UK-GBC, 2018; Li et al., 2019; Choi et al., 2019). Buildings are major consumers of energy and emitters of greenhouse gases, contributing to climate change during all life cycle stages. Worldwide, building construction and operation is responsible for 36% of global energy use and 39% of greenhouse gas emissions (GHGs) (IEA, 2018). While most of these figures relate to building operation, the construction stage also has a role to play in reducing energy use and mitigating climate change. According to the U.K. Green Building Council (UK-GBC, 2018), the construction industry uses more than 400 million tons of material per year, the majority of which has an adverse impact on the environment. For example, 60 million tons goes directly to landfill simply due to over-ordering, mis-ordering or poor handling and breakages. Moreover, the U.S. construction industry accounts for 160 million tons, or 26%, of non-industrial waste generation each year (EPA, 2009). It additionally contributes to 23% of air pollution emissions, 50% of GHGs , 40% of drinking water pollution and 50% of landfilled waste (Willmott Dixon Group, 2010).

In Israel, construction waste forms about 60% of the total solid waste. It consists mainly of concrete, steel reinforcement, steel sections, blocks, tiles, wood, plastic materials, gravel, and soil (Katz and Baum, 2011). The finishing phase in construction generates about three times more waste relative to the construction of the structural frame (Baum and Katz, 2004). The amount of construction waste exceeds 7 million tonnes each year (Gabay et al., 2014). This has raised the importance of possible management alternatives such as reusing and recycling construction and demolition materials along with more effective management of construction and demolition waste (CDW) and construction processes. Also, it raised the importance of implementing innovative management approaches like lean construction and BIM in reducing different types of construction wastes (Cheng et al., 2015; Maraqa et al., 2020; Maraqa et al., 2021; Maraqa et al., 2021).

There is a growing trend among governments, clients, design firms, and construction companies to recapture value from CDW. Several countries in Europe like Denmark, Holland, and Belgium recycle 80-90% of their construction wastes (Symonds et al., 1999). Unlike some European cities, Israel recycles about 20% only, with the remainder disposed in legal and illegal landfilling sites (Katz and Baum, 2011).

The material passport (MP) is a quantitative and qualitative documentation of the materials composition of a building, displaying materials embodied in buildings as well as showing their recycling potential and environmental impact, which in turn gives them value for recycling and reuse (Honic et al., 2019). In a nutshell, the MP can turn buildings into future “databanks” (BAMB, 2020; Heinrich and Lang, 2019; Rose and Stegemann, 2019).

Honic et al. (2019) demonstrated a proof of concept for a material passport on a residential building in Vienna. They evaluated two variants, variant in timber and variant in concrete. The assessment carried out for exterior walls, roof, ceilings and windows. The concrete variant consists of load bearing elements made of concrete, EPS insulation, windows with an aluminium frame and a plaster façade. The timber variant consists of load bearing elements made of cross laminated timber (CLT), the outside façade is wooden, and most of the building components consist of a wood fiber insulation and the windows have a wooden frame. They found that the total recycling potential of the concrete variant is 52% while the timber variant is 34%. However, if the total mass is taken into consideration the timber variant leads to a lower waste generation compared to the concrete variant. The timber variant is associated with 1123 tonnes of waste, while the concrete variant is associated with 1797 tonnes of waste. Also, they compared the life cycle assessment (LCA) results of the two variants and found that the timber variant has lower environmentalimpact than the concrete variant. The acidification potential (AP) and the primary energy intensity (PEI) metrics are three times higher in the concrete variant compared to the timber variant at year 0 (new building construction) and year 100 (building end-of-life).

The material passport research by Honic et al (2019) was executed on a hypothetical building, not on a real building relevant to buildings in Austria. There are several obstacles and challenges when applying these concepts to real buildings. One is the lack of detailed material composition in early design stages. Also, this work is limited to the design stage, and does not cover the construction and demolition phase, the latter of which is very critically connected to any future effort to recover materials from the building. Finally, while their case study is restricted to Austria, there are some challenges in generalizing the case so that it can be tested in other countries.

This paper aims to develop a BIM material passport for a LEED gold-rated commercial construction project in Tel Aviv. The material passport will help in identifying the different materials used in the construction project. Mass distribution within the building, the share of recyclable and waste materials, and the total amount of global warming potential (GWP), acidification potential (AP), and primary energy intensity (PEI) originating from the incorporated materials.

2. Methods

A case study research method is used to develop a material passport for a commercial building. It combines building information modelling (BIM) and material flow analysis (MFA) to define a material passport for a LEED-rated commercial building in Tel Aviv, Israel. The building was designed using “BIM in the big room”, a product development technique in which designers of different sub-systems are brought together to promote communication, collaboration, and short-cycle problem-solving (Sacks et al., 2018). For this finished building, BIM in the big room involved architects and structural, mechanical, and electrical engineers collaborating to optimize the design of the building. Material passports use BIM to classify and quantify building objects by their material constituent to assess their potential for recycling at the building’s demolition stage. The material passport can be combined with life cycle inventory data to evaluate the environmental impacts of the embodied material in the building and also guide best practices for deconstruction. Life cycle assessment following (ISO 14040/44, 2006) implemented to quantify GHGs, acidification potential (AP), and primary energy intensity (PEI) for each material. Stadel et al. (2011) outlined the potential for combining BIM and LCA tools. These concepts can be coupled with MFA tools as noted by Honic et al. (2019a) with the material passport. The main outcomes of the material passport are the mass distribution within the building, the share of recyclable and reusable material, and the total amount of GWP, AP, and PEI.

To evaluate the project's environmental effects, each element is modeled to the exact materials and dimensions using BIM. For each element, we allocated the recycling weight, life span, density, separability of materials layers, and accessibility for the materials. Data are required from the construction department in the company. The data includes all the architecture, structural, mechanical and electrical BIM models, material suppliers, the life span for each material, quantities of actual material delivered to the site, and the amount of waste delivered to the landfill during the construction phase (Figure 1). The materials covered in this study are concrete materials, HVAC ducts, firefighting pipes, HDPE pipes, concrete block, gypsum drywall, gypsum blocks, tile, system panel, aluminium mullion and glass. The reason for selecting these materials because they are available within the BIM model, we got from the company that constructed this project.

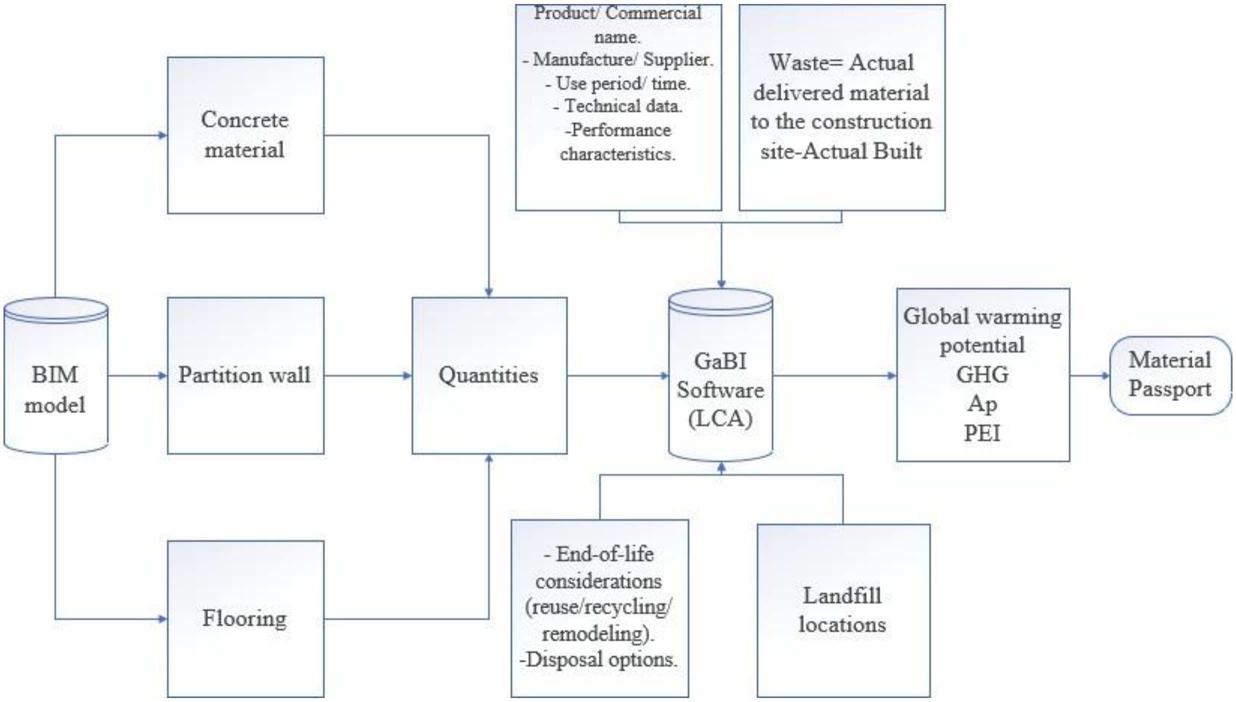

Figure 1. Methodology for the compilation of the Material Passport.

The functional unit in this project is defined as a square meter of built space of a commercial green LEED-Gold rated building with an approximate area of 50,000m2. The building consists of different materials like concrete, aluminum, glass, high-density polyethylene pipe (HDPE), concrete block, cast iron pipes, gypsum plasterboard, gypsum block, ceramic tiles, steel ducts, and steel cable trays.

LCA model was built using GaBi (PE-international 2012) which is a product system modelling developed by a Germany company called PE INTERNATIONAL. GaBi is considered as one of the leading software for building life cycle assessment models (Herrmann and Moltesen, 2014). In this study an LCA model includes all the materials and their quantities with the associated transportation (Figure 2). The transportation distance is assumed to be 30 km from the construction site.

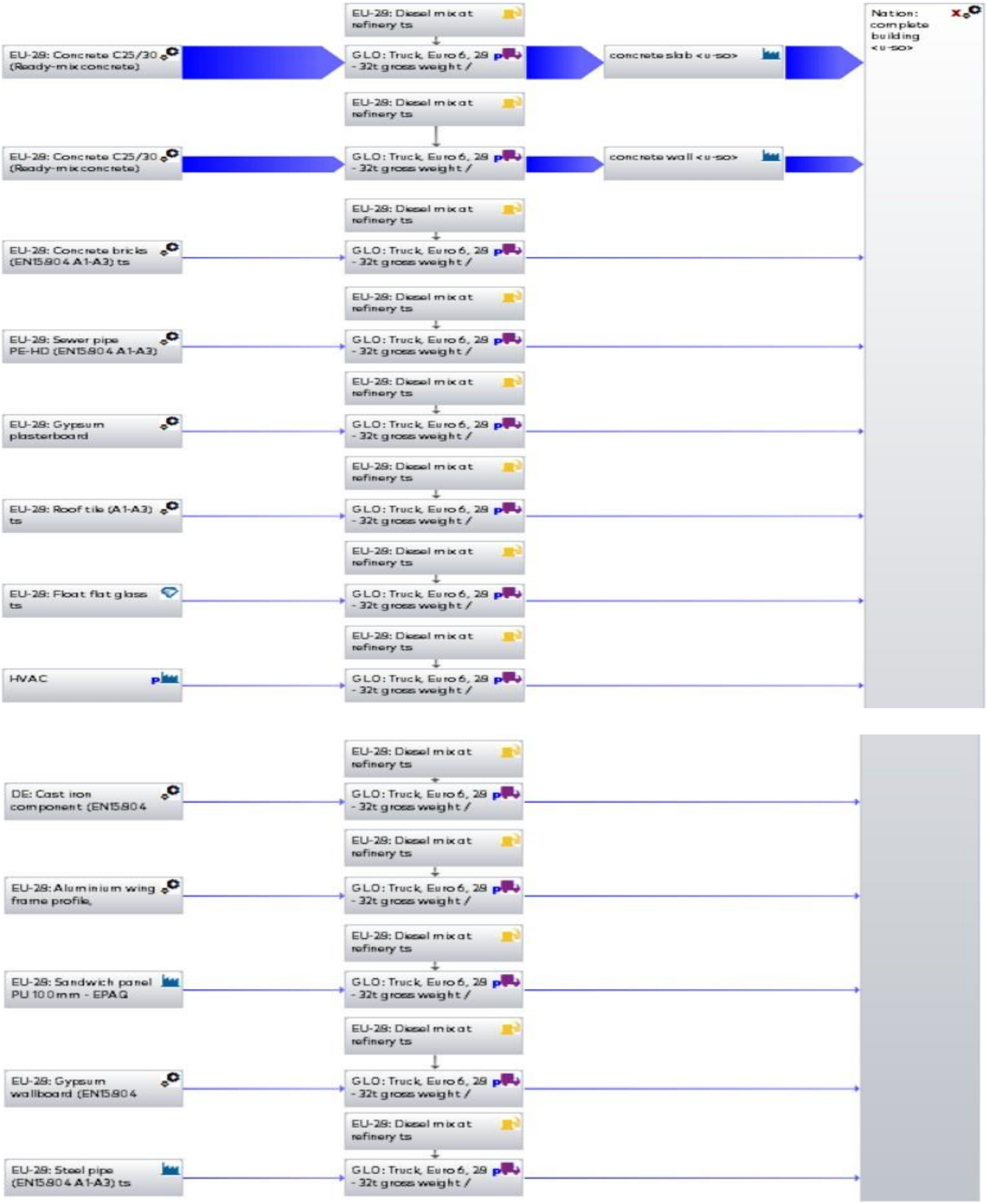

Figure 2. System boundary for life cycle assessment for the construction project

3. Results

The construction building was assessed based on the building components obtained from the BIM model. Each material was classified for each life span and density (Table 1). Some of the materials have constant densities like concrete, concrete block, and gypsum block. Other materials like HVAC ducts, HDPE pipes, cable trays, and firefighting pipes have variant diameters depending on the diameters. For these materials, the densities were calculated by multiplying each different diameter with the corresponding density. The recycling weight for each material was determined from the literature based on a study executed by (Honic et., 2019). Recycling weight 1 means that 75% of the material is recycled while 25% is waste. Recycling weight 2 means that 50% of the material is recycled while 50% is waste.

Table 7. The life span for different materials used in the project with their associated densities

Materials	Life Span (Years)	Density (Kg/m^3)	Density (Kg/m^2)	Density (Kg/m)	Recycling weight
Concrete slabs	100	2400			2
Concrete columns and walls	100	2400			2
Concrete Block	100	2200			2
Gypsum Block	50	850			2
Gypsum drywall	50	530			3
Tile	75	1800			2
HVAC duct	50		6.4		2
HDPE pipe	50			0.113-20.35	2
Firefighting pipe	25				
Aluminum Mullion	60	2710			1
Curtain walls (Glass)	60				1
Steel Panel	20		12.9		1

The BIM model built for this project used to schedule the quantities for the different elements (Table 2). The mass at time 0 represents all the material implemented at the completion of the construction phase. These quantities were input for the GaBi software to calculate the environmental impacts for each material at time 0. From the GaBi software the environmental impacts for the different materials were calculated based on the data stored within its database and represented by GWP, AP, and PEI.

Table 8. Material mass distribution at time 0 and their environmental impacts.

Materials	Mass at time 0 (ton)	GWP time 0 (Kg CO_2 eq/m^2)	AP time 0 (Kg SO_2 eq/m^2)	PEI time 0 (MJ /m^2)
Concrete slabs	74,816	71.60	0.1030	439.0
Concrete columns and walls	34,684	34.60	0.0497	213.0
Concrete Block	384	0.43	0.0007	3.3
Gypsum Block	1,540	0.51	0.0003	77.9
Gypsum drywall	2	0.01	0.0000	0.11
Tile	2,253	7.87	0.0061	154.0
HVAC duct	116	43.00		-
HDPE pipe	71	1.50	0.0025	63.6
Firefighting pipe	89	2.10	0.0019	39.8
Aluminum Mullion	30	3.43	0.0111	67.2
Curtain walls (Glass)	913	11.30	0.0736	166
Steel Panel	14	0.59	0.0015	10.8
Total	114,915	180.58	0.2530	1235.3

Figure 3 shows the share of the various materials at time 0. The percentage for each material is calculated by dividing its weight by the total material weight. Concrete material includes concrete columns and walls, and the concrete slab is the dominant material. It exceeds 95% of all the materials in the building. Using the global warming metric, the GWP for concrete material is 106.2 Kg CO_2eq/m^2. The AP is 0.153 Kg So_2 eq/m^2. The PEI is 652 MJ/m^2.

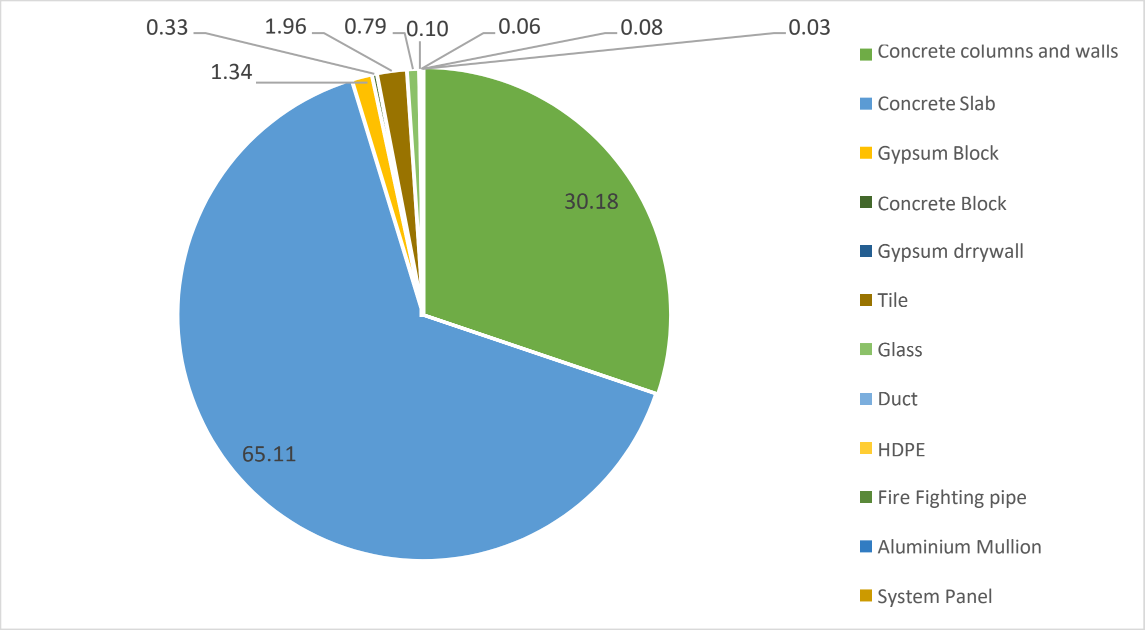

Figure 3. Share of the materials for the construction project at time 0

Table 3 represents the mass at time 100 which includes all the materials implemented during the whole life of the project this includes the material that replaces twice, triple, and until fourth-folds. These quantities were input to the GaBi software to calculate the environmental impacts for each material at time 100. From the GaBi software the environmental impacts were calculated for the different materials and represented by GWP, AP, and PEI.

Table 9. Material mass distribution at time 100 and their environmental impacts

Materials	Mass at time 100 (ton)	GWP time 100 (Kg CO_2 eq/m^2)	AP time 100 (Kg SO_2 eq/m^2)	PEI time100 (MJ /m^2)
Concrete slabs	74,816	71.60	0.1030	439.0
Concrete columns and walls	34,684	34.60	0.0497	213.0
Concrete Block	384	0.43	0.0007	3.3
Gypsum Block	3,080	1.02	0.0006	156.0
Gypsum drywall	5	0.010	0.0000	0.2
Tile	4,506	15.70	0.0122	307.0
HVAC duct	232	86.00	-	-
HDPE pipe	143	3.00	0.0050	138.0
Firefighting pipe	356	9.31	0.0077	159.0
Aluminum Mullion	60	6.87	0.0222	134.0
Curtain walls (Glass)	1,826	22.60	0.1470	332.0
Steel Panel	71	2.96	0.0074	54.1
Total	120,174	262.50	0.3720	1938.6

Figure 4 shows the share of the various materials at time 100. Concrete material that includes concrete columns, walls, and concrete slab represents the dominant material. It exceeds 90% of all the materials in the building. The GWP for the concrete material is 106.2 Kg CO_2eq/m^2. The AP is 0.153 Kg So_2 eq/m^2. The PEI is 652 MJ/m^2. Gypsum block represents the second material in the building after concrete, and this is due to a large number of partition walls in the building. The gypsum is high recyclable material, which means that most of the gypsum blocks at their end of life will be grind and reused for manufacturing new gypsum blocks.

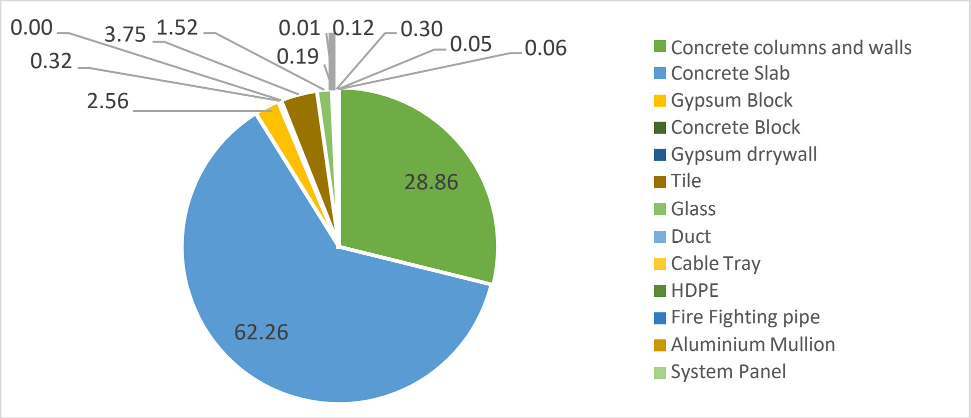

Figure 4. Share of the materials for the construction project at time 100

Figure 5 shows the accruing masses during the life cycle of the building, whereby the first building elements need to be exchanged in the year 20. As each material has its lifespan, it is substituted at a different point in time, and therefore the masses accrue at varying times. Thus, each material is also recycled or disposed of at a specific time. From figure 5, it is clear that during the building life cycle, there will not be significant replacement of the building's elements, because the dominant material is concrete which will be replaced at the building's end of life.

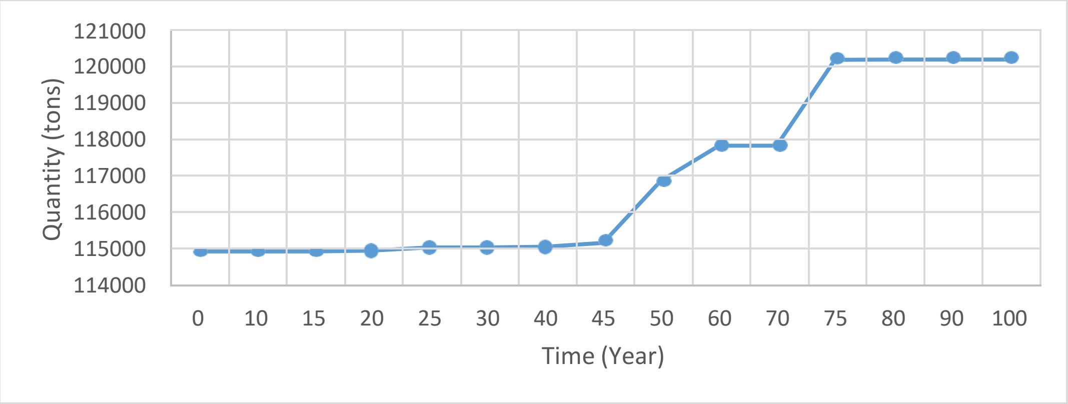

Figure 5. Accruing masses during the life cycle of the building (100 years)

5. Conclusions

The construction project studied herein demonstrate the importance of building material passport in showing the embodied materials in the building during the whole life cycle. The material passport gives a unique opportunity to the engineers to identify the environmental impacts for all the building elements during the construction phase and at the building's end of life. This can help in optimizing the materials that have low recycling potential and have a lot of hazards to the environment. Moreover, it allows completing the material flow analysis and selects the best method to process each material at its end of life and identify to which secondary market it should be delivered.

Based on the results obtained from this case study, the concrete material is the dominant material at the time 0 and time 100. It corresponds with around 95% and 90%, respectively. Concrete has a negative environmental impact. Its major constituent cement is a major emitter of GHGs. Moreover, at end-of-life, concrete is used as a filling material or base course, which is a low value material. Results from this study encourage using lightweight materials like wood and steel, which also have a lower environmental impact, and more recycling potential.

This research presents a material passport for a commercial construction project by displaying the embodied materials and their environmental impacts. There are many limitations and challenges to get data from construction companies to calculate the material waste during building construction. The material waste during construction is calculated by subtracting the actual material built from the actually delivered materials. Lack of data about the characteristics and properties of some materials leads to making certain assumptions and relies on data from the literature. A major challenge in this research is reliance on European LCA data for the analysis; this underscores the necessity to create a country-specific database for the materials available in the local market.

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