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Life Cycle Analysis of Vertical Building Extensions – Environmental Impacts of Different Material Selection

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Abstract. Adding storeys to existing buildings plays a large role in sustainable urban densification and helps to decrease the growing demand for urban city housings. Vertical building extensions create living space without the need for further land use, by extending existing buildings vertically by one or more storeys. Research points to the possibility of creating 1.1 million homes through storey additions in German metropolitan areas. A common method for investigating environmental impacts of a building is a life cycle assessment (LCA). Because of vertical building extensions being a relatively new concept, research is lacking, especially for LCAs. Therefore, this study describes frameworks and rules for LCAs of vertical building extensions. Moreover, environmental impacts of different material selection within storey additions are investigated. For this, a realised storey addition is analysed and main construction materials of the exterior wall and roof are replaced. The environmental impacts of material selection are then compared using the impact category global warming potential. Results show that the choice of material has a large influence on LCA results. In this case, the wood construction has the lowest greenhouse gas emissions and amounts to approximately 180 kg CO_2 eq/m². The highest greenhouse gas emissions are emitted by a steel construction with approximately 230 kg CO_2 eq/m².

1. Introduction

1.1. Vertical building extensions

In Germany's large cities and metropolitan regions, the number of inhabitants is rising continuously and is expected to carry on doing so in the future. As a result of this increase in the urban population, rental prices are rising, accelerating the process of gentrification in some areas. Due to insufficient construction activity in recent years, urban living space is urgently needed. Additionally, the Federal Government calls for a reduction in the daily land use through construction measures and for a climate-neutral building stock by 2050. [1]

Cities and towns can use the existing infrastructure while, at the same time, increasing the number of available dwellings, by using redensification methods. The increase in the number of apartments results in a potential of approx. 1.1 million apartments to be built, cost-effectively, in areas with a great housing shortage in Germany. [2] However, increasing the height of a building requires careful planning, as several problems arise with it. These include physical building problems, in particular, relating to fire protection, static load reserves of the existing building and other building law aspects that have to be solved prior to an increase in height. [3]

From an environmental point of view, vertical building extensions are a useful way of creating living space in urban areas. Through the continuous use of large parts of the building stock, environmental impacts for the production of the load-bearing structures are entirely saved. In addition, no new land has to be sealed, but existing building land can be used. The simultaneous energetic refurbishment of an existing building offers high potential for energy savings. Besides that, the choice of material, used for the building extensions plays a role in reducing environmental impacts, which will be examined in this study.

1.2. Life Cycle Assessment of buildings

In order to be able to describe environmental impacts of constructions, environmental assessments are carried out. Under certain calculation rules, these can also be carried out for vertical building extensions. According to DIN EN ISO 14040, life cycle assessments are defined as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". [4]

LCAs in the building sector are covered by the standard EN 15978 "Sustainability of buildings - Assessment of the environmental quality of buildings". With the aim to cover the entire life cycle of buildings, from the manufacture of the individual components to the demolition and disposal or recycling of the materials. The framework of a LCA consists of the phases defined in accordance with DIN EN ISO 14040. [5]

For the environmental assessment of building construction DIN EN 15804 defines various life cycle phases. These phases range from the manufacturing and construction phase (module A) through the use phase (module B) to the disposal phase (module C). In addition, it is possible to include credits and debits from other systems by re-using materials outside the actual life cycle of the building (module D). [6] As Figure 1 shows, the individual phases are subdivided into smaller units. Former research shows that construction material selection plays a high role in LCA results. [7]

In this paper a methodological approach for LCAs of vertical building extensions will be shown and applied to an existing project. In a second step, the influence of the material exchange of main materials of a vertical building extension on the result of an environmental assessment, will be examined.

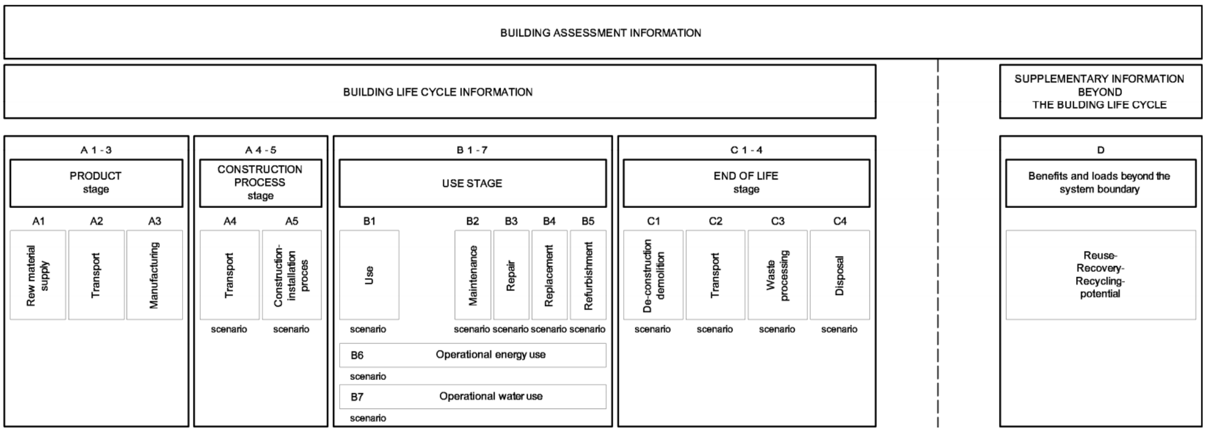


Figure 1. Life cycle stages for building assessment (DIN EN 15804) [6]

2. Methodical approach for vertical building extension LCA

At the present time, research on LCA of vertical building extensions is lacking. A study by the Technical University of Dortmund shows that an increase in height has a lower environmental impact per m² than a demolition and new building. [8] While evaluation methods for renovation and refurbishments have developed, no valid procedure for vertical building extensions exist. [9–12]

In order to calculate vertical building extension LCA, it is necessary to draft basic assumptions regarding the handling of the individual life-cycle modules of the components. This makes it possible to compare further LCA of vertical building extensions. The main premises for this are presented in the following section.

Vertical building extensions extend the service life of the building, for which the reference value, as for new building, was set at a further 50 years. In the course of vertical building extension, large parts of the building are often dismantled and removed. Components for this are calculated as end-of-life in module C at the time of the construction of the extension. After the extension, the building substance consists of two different parts. On the one hand, there are materials that were added to the building in the course of the extension work. This includes the extension itself, as well as all parts added, such as facade insulation, which are analysed in module A. On the other hand, there are existing materials that were already installed in the building before the vertical building extension that will remain in place. During the use phase of the building, the replacement of both the new building parts and the existing materials is evaluated. In order to be able to evaluate replacement cycles, the table "Service lives of building components" is used for life cycle analyses according to the Sustainable Building Assessment System (BNB), published by the German Federal Ministry of the Interior, Building and Community. [13] The replacement cycles are set to zero at the time of the extension and both the replacement of existing and new building materials in the further life cycle are calculated.

At the end of the lifecycle, all components of both the existing building stock and the extension are evaluated in module C. The calculation of the operational energy use of module B6 is continued throughout the entire lifecycle. Figure 2 graphically shows the methodology.

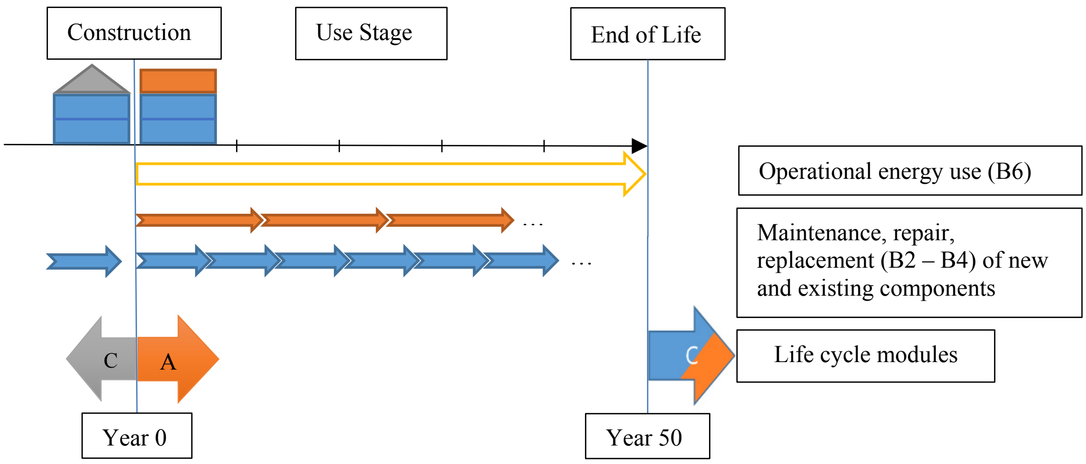


Figure 2. Method for Life cycle assessments of building extensions

3. Application of the method

3.1. Exemplary building

In order to investigate the potentials of vertical building extensions, an actual extension was examined in depth. The building was constructed in 1957 and is located in Western Germany. The building consists of two identical, mirrored, individual buildings; each containing four units. In addition to the examined building, other buildings of the same type within the settlement were also extended at the same time. Before the extension, the existing buildings showed a high need for renovation. It was decided to carry out a vertical building extension with facade renovation and construction of new balconies. The walls of the extension are made of prefabricated brickwork; and the new roof is a wooden monopitch beam roof. The existing saddle roof, which was used as a floor for drying clothes and not insulated, was removed. The existing tenants remained in the building during construction, were compensated by rent reductions and were regularly provided with information on construction progress. As a result, the tenants were able to live in a better-insulated apartment with a significantly enhanced character of the building. In addition to the extension and renovation of the façade a small garden was added on the ground floor. The total living space extended from 521.4 m² in four units to 786.5 m² in eight units.

Figure 3. Building before the extension

Figure 4. Building after the extension

3.2. Heating energy demand
Although there is more room to be heated after the extension, the annual primary energy requirement for heating decreased overall, due to the better insulation of the building shell. From an absolute amount of 63 429 kWh/a, the annual primary energy requirement was reduced to 41 054 kWh/a for the entire building. The comparison becomes even clearer when this improvement is considered in relation to the living space. While the annual demand for heating energy was approximately 121.7 kWh/m²a before the extension, it is now approximately 52.2 kWh/m²a. These results show that vertical building extensions can also lead to a reduction of primary energy for the whole building.

3.3. Database and Software
In order to make LCA results comparable, there are databases in which the environmental impacts of individual building materials are described. In this paper the German database oekobau.dat is used. This database is published by the Federal Ministry of the Interior, Building and Community and completely complies with the standard EN 15804. [6, 14] Calculations for this paper were performed using the LCA-tool LEGEP, a software especially designed to display the life-cycle of buildings. [15] The program uses the oekobau.dat as a background database. Calculations are limited to a German context.

4. LCA results of different impact categories
Table 1 shows the overall result of the LCA of the built extension. The life cycle modules A, B and C as well as the building components are presented in relation to the four environmental indicators global warming potential, acidification potential and the consumption of primary energies, divided by their origin from renewable and non-renewable sources. Module D was not considered.

Table 1. LCA Results of the built vertical building extension

	GWP [kg CO2-eq/m²GEA]			AP [kg SO2-eq/m²GEA]			PERT [MJ/m² GEA]			PENRT [MJ/m² GEA]		
Module	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Foundation	0	0	1	0.00	0.00	0.01	0	0	1	0	0	17
Exterior Wall	25	5	7	0.08	0.02	0.01	30	6	1	305	103	18
Interior Wall	16	6	4	0.03	0.03	0.01	15	19	-2	220	110	29
Ceiling	6	5	12	0.01	0.02	0.02	14	24	3	68	78	39
Roof	-4	6	49	0.09	0.06	0.00	314	97	-442	297	164	4
Flooring	2	3	13	0.00	0.02	0.00	4	54	-8	39	111	7
Stairs	0	0	0	0.00	0.00	0.00	0	0	0	0	5	2
Windows	4	8	11	0.02	0.07	0.00	24	56	-87	66	166	4
Doors	0	2	9	0.01	0.01	0.00	16	8	-75	20	42	1
Balconies	7	1	1	0.02	0.01	0.00	6	2	0	66	19	4
Others	0	1	0	0.00	0.01	0.00	0	4	-9	0	23	9
Technical Equipment	3	7	10	0.01	0.02	0.00	3	7	1	61	126	4
Building	**59**	**32**	**118**	**0.28**	**0.16**	**0.06**	**426**	**175**	**-617**	**1 143**	**635**	**138**

Results show that the roof construction has a major influence on the overall result for each indicator, followed by the exterior wall. For this, Figure 5 shows the influence of the individual building components and the individual modules on the global warming potential. It can be seen that the wood roof construction has the greatest influence on the result, followed by the exterior wall. The negative figure, in the production of the roof, results from the carbon stored in the wood. This carbon is released again in module C. The high value of module C is mostly due to the release of carbon from the existing wooden roof structure at the time of construction as well as the demolition of the roof after 50 years.

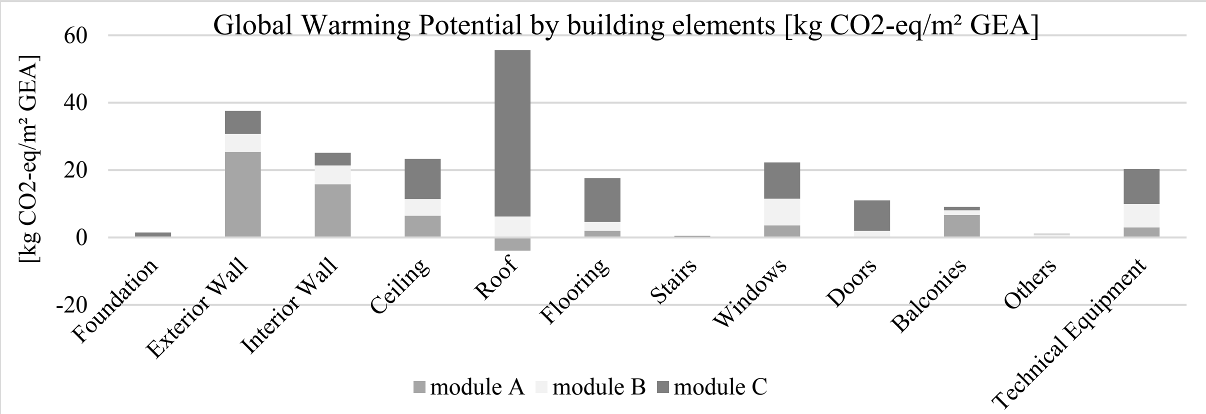


Figure 5. Global Warming Potential of different materials through the life-cycle

5. LCA results of exchanged materials

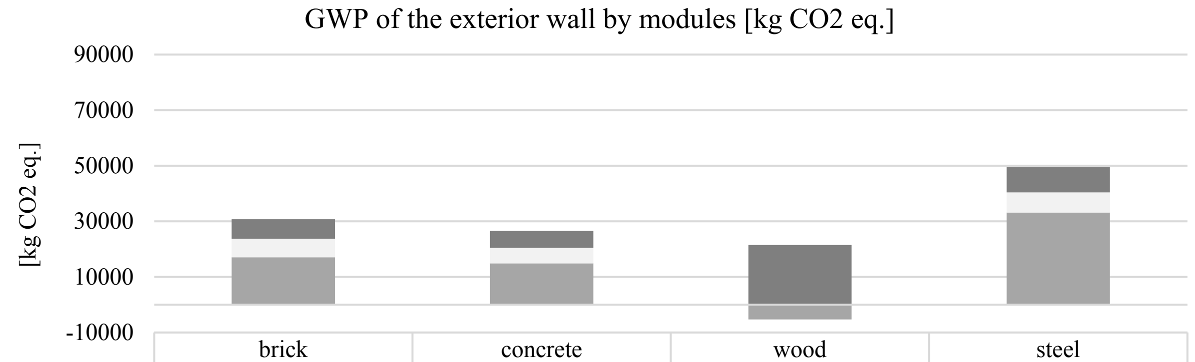
In order to demonstrate the impact of different material selection, the building elements have been replaced and environmental impacts are shown. The exterior wall of the building extension and the roof have been replaced by common building methods from a brick, reinforced concrete, wood and steel construction. Table 2 shows the chosen constructions and their main components from exterior to interior. The exterior wall of the building extension has a size of 166.50 m² as the roof is 330.63 m² large. To eliminate the influence of the heating energy during the use-phase of the building, *U*-values for the exterior wall and the roof have been set to 0.20 W/m²K.

Table 2. Chosen vertical building extension constructions

Material	Exterior Wall	Roof
Brick	- 16 cm polystyrene thermal insulation composite system, fining coat - 17,5 cm calcareous sandstone - interior lime plaster and painting	- slab covering - 21 cm hanging bricks - 18 cm Bitumen membrane water-proofing, polystyrene thermal insulation - interior lime plaster and painting
Reinforced Concrete	- finish coat and painting - 16 cm polystyrene thermal insulation composite system - 20 cm reinforced concrete C20/25 thickness - interior thin-plaster and painting	- slab covering with 20 cm polystyrene thermal insulation - 12 cm reinforced concrete plate thickness - Bitumen membrane waterproofing - interior lime plaster and painting
Wood	- Ventilated board-on-board wood siding - 16 cm wood frame construction with 16 cm mineral wool insulation between frames - 4 cm mineral wool service cavity - Gypsum board and painting	- Metal coping, Plywood board - 18 cm Laminated timber construction with mineral wool thermal insulation - Gypsum board with latex paint
Steel	- External wall cladding with metal cassettes as sandwich elements with 6 cm PUR insulation - Steel construction HEA 140 mm - 14 cm mineral wool insulation with OSB-board - Gypsum board and painting	- Metal coping - 5 cm mineral wool insulation - Steel structure HEA 120 mm with mineral wool insulation, gradient roof - Gypsum board with latex paint

5.1. Results

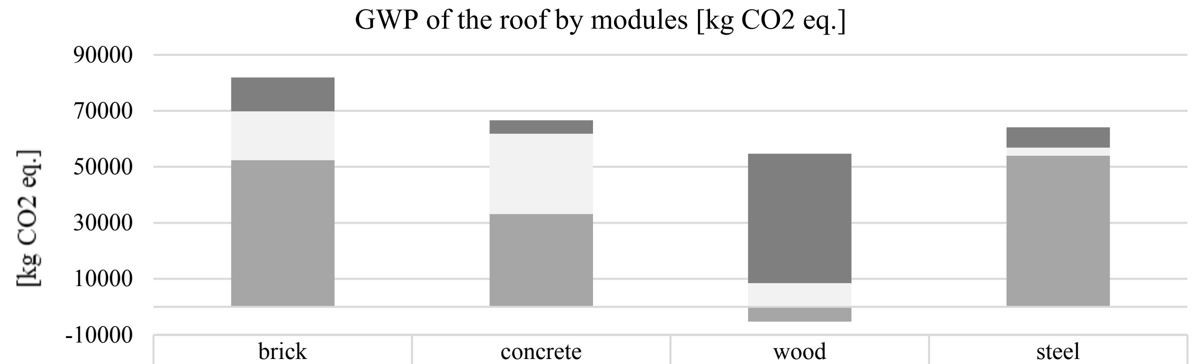
Figure 6 shows the global warming potential (GWP) of the individual exterior wall construction according to life cycle modules. It can be seen that the production for all exterior walls has a high influence on the overall result, while maintenance shows to have a low influence. The influence of module C is approximately the same for the construction materials except for wood, which has a particularly high GWP in module C. This is mainly due to the carbon stored in the wood and negative value in module A and the clearance in module C. The sum of the individual life cycle modules shows that wood has the lowest GWP with 16 154 kg CO_2-eq. in these external wall constructions, while the steel construction has the highest share with 49 563 kg CO_2-eq. due to a very high proportion of emission in the production phase.



	brick	concrete	wood	steel
module C	6989	6069	21260	9138
module B	6671	5584	211	7272
module A	17067	14899	-5317	33153

Figure 6. Results of different exterior wall materials

Figure 7 shows the global warming potential of the roof constructions. Compared to the exterior wall results, the steel roof construction has a lower carbon share and the highest emissions are caused by a brick variant with approximately 81 910 kg CO_2-eq. The wooden roof triggers the lowest GWP with 49 363 kg CO_2-eq. Both brick and steel constructions show a high GWP in module A.



	brick	concrete	wood	steel
module C	12067	4769	46224	7283
module B	17412	28662	8453	2813
module A	52431	33180	-5314	54045

Figure 7. LCA results of different roof constructions

In a final step, it is shown which influence the choice of material has on the result of the entire building. Figure 8 shows the LCA results of the entire vertical building extension and the effects of the different constructions over the entire life cycle as well as the built variant made of a mixture between wood and brick. It can be seen that vertical building extension made of wood has the lowest CO_2 equivalent (182.43 kg CO_2 eq/m² GEA). The highest impact is caused by an exterior wall and roof construction made of steel (227.60 kg CO_2 eq/m² GEA).

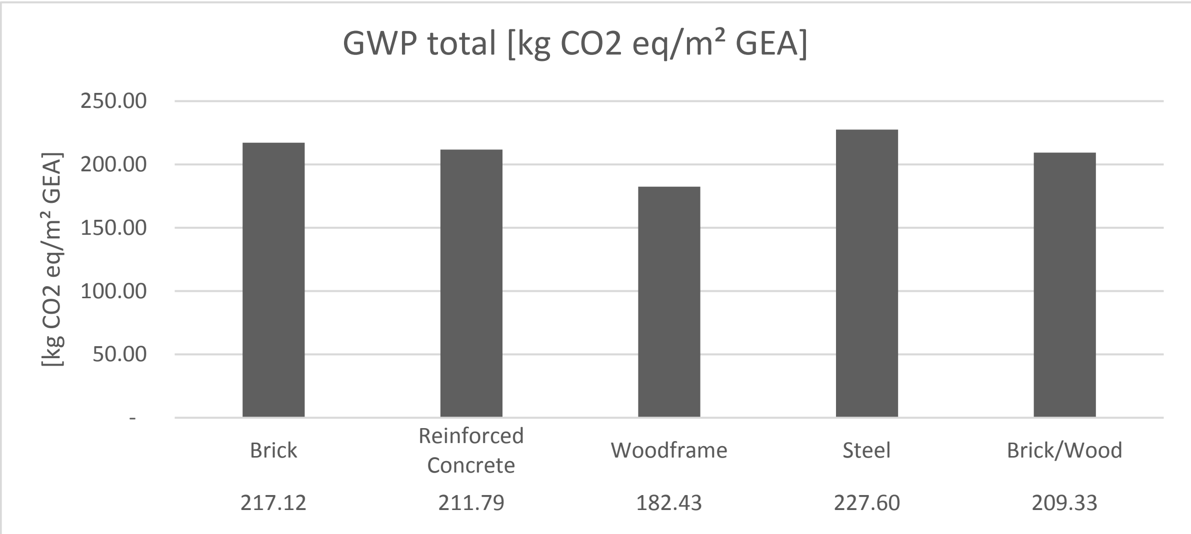


Figure 8. Global Warming Potential results for the entire building

6. Conclusion

Vertical building extensions are a useful tool to counteract inner-city housing shortages. The continued use of existing structures, the avoidance of new space sealing as well as the saving of heating energy result in high ecological potentials. In this paper, a procedure for the environmental assessment of vertical building extensions was developed and applied on an example building. Results showed that external walls and the roof have the greatest influence on LCA results. In a second step, the influence of different constructions made of different main materials was examined in more detail. The constructions made of brick, reinforced concrete, wood and steel were presented and the results were examined with regard to the LCA results. It has been shown that choice of materials has an important influence on the LCA results. For the investigated GWP it was found that wood constructions with about 182 kg CO_2-eq/m² GEA cause the lowest greenhouse gas emissions over the entire life cycle whereas the highest greenhouse gas emissions are caused by a building extension of a steel construction with 230 kg CO_2-eq/m² GEA. In order to verify these results, future research should investigate other vertical building extensions. It is also possible to divide the end of life components into two different scenarios; where one scenario displays the demolition at the time of construction and the other, the demolition at the end of the life cycle after 50 years. On further consideration, the comparison between the demolition of a building followed by a new construction, compared with a vertical building extension, could be carried out.

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