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Life cycle assessment of cost-optimized buttress earth-retaining walls: a parametric study

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Abstract

In this paper life cycle assessments are carried out on 30 optimized earth-retaining walls of various heights (4–13 m) and involving different permissible soil stresses (0.2, 0.3 and 0.4 MPa) in Spain. Firstly, the environmental impacts considered in the assessment method developed by the Leiden University (CML 2001) are analyzed for each case, demonstrating the influence of the wall height and permissible soil stress. Secondly, this paper evaluates the contribution range of each element to each impact. The elements considered are: concrete, landfill, machinery, formwork, steel, and transport. Moreover, the influence of the wall height on the contribution of each element over the total impact is studied. This paper then provides the impact factors per unit of concrete, steel, and formwork. These values enable designers to quickly evaluate impacts from available measurements. Finally, the influence of steel recycling on the environmental impacts is highlighted. Findings indicate that concrete is the biggest contributor to all impact categories, especially the global warming potential. However, the steel doubles its contribution when the wall heights increase from 4 m to 13 m. Results show that recycling rates affect impacts differently.

Keywords: Life cycle assessment, Retaining Wall, Sustainability, Buttressed wall.

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1. Introduction

Following the success of the 21st Conference of the Parties on the issue of climate change and a worldwide agreement involving almost 200 nations (Ji and Sha, 2015), the environmental impacts of the construction sector, which is known to be one of the most carbon-intensive sectors (Ramesh et al., 2010), is becoming increasingly important. In particular, structures that use large amounts of cement, the production of which incurs large carbon dioxide emissions due to limestone calcination and high energy demands (5% of total energy consumption according to Boesch and Hellweg, 2010), are critical. Accordingly, research in this field has focused on the sustainable construction practices implemented by construction companies (Serpell et al., 2013; Yusof et al., 2016), the embodied energy of construction projects (Wang and Shen, 2013; Wang et al., 2012) and the life cycle greenhouse gas emissions of concrete structures (Barandica et al., 2013; García-Segura et al., 2014).

Earth-retaining buttress walls made of reinforced concrete (RC) are common structures in civil engineering. Various design factors influence the appearance and, consequently, the performance with regard to life span, cost or environmental impact. The design process itself is mostly based on the experience of the engineer using a trial-and-error approach to achieve an appropriate solution. Often these solutions, though compliant with structural codes, do not represent the optimal solution with respect to current design objectives (cost, service life, environmental embodied impacts) thus leaving room for optimization. To this aim several studies attempted to find the best heuristic-based solutions for RC structures, such as building frames (Li et al., 2010), columns (de Medeiros and Kripka, 2014; Park et al., 2013), footings (Camp and Assadollahi, 2015), prestressed concrete bridges (García-Segura et al., 2015; García-Segura et al., 2016; Yepes et al., 2015) and earth-retaining walls (Yepes et al., 2012). Parametric optimization studies on cantilever earth-retaining walls, based on the type of ground fill and soil permissible stress (Yepes et al., 2008; Yepes et al., 2012) showed that cost and global warming potential are closely related. Along this same line, Martí et al. (2016) found that the cost and embodied energy of both precast-prestressed concrete U-beam road bridges criteria were dependent.

The majority of these studies aimed at identifying the lowest cost and carbon emissions while neglecting environmental impacts other than embodied carbon. Despite carbon emission being the most prominent impact factor to mitigate as a main contributor to global warming, this paper includes the following five midpoint impact categories (as specified in the calculation model CML 2002 (Guinée, 2002)): depletion of abiotic resources, the acidification of the environment, the eutrophication of water bodies, the depletion of the stratospheric ozone layer, and the photochemical ozone creation often defined as summer smog. Life cycle assessment (LCA) is a complex multi-parametric assessment of the environmental impact of a structure over its whole life cycle.

Previous LCA parametric studies analyzed the environmental burdens in civil engineering based on optimal practical solutions. Sanjuan-Delmás et al. (2015) studied the impact of geometrically optimized water tanks in terms of water capacity and dimensions for three ground positions in a parametric assessment. Other LCA studies are based on parametrical approaches

(Bonamente et al., 2014; Dijk et al., 2014) and highlight the need for intermediate life-cycle approaches at the construction sector (Hollberg and Ruth, 2016).

Decisions on the structural design of civil constructions, in this case earth-retaining buttress walls of reinforced concrete, can have impacts on the complete life cycle of the product. Hence, this paper is devoted to assessing the environmental impacts of 30 cost-optimized walls, considering a recycling rate of reinforcement steel of 70 % and the electricity mix available in Spain. A life cycle framework from upstream processes and by-products recycling (steel) of an earth-retaining buttress wall is modeled and assessed through LCA based on international standards of series ISO 14040 and ISO 14044 (ISO, 2006). The processes considered are the excavation at the raw material quarries, the transportation and processing of materials, the installation with different machines as well as the demolition at the end of life.

2. Materials and methods

The goal of the LCA is to provide a magnitude order on the environmental burdens of each stage of the life cycle of earth-retaining buttress walls of reinforced concrete. The system includes the activities of concrete production, steel production, transportation, use of machinery for installation and demolition, processing of landfill, and formwork production. The LCA of the earth-retaining wall has been carried out in agreement to EN ISO 14040:2006 (ISO, 2006). The assessment method CML 2001 developed at the Leiden University (Centrum voor Milieukunde) (Guinée et al., 2002) is used. The LCA has been modeled using the Ecoinvent database 3.2.

2.1. Assumptions of the dataset and limitations

The choice for Ecoinvent (Frischknecht and Rebitzer, 2005) is based on the widespread use and scientific reliability (Pascual-González et al., 2016). Last authors stated that Ecoinvent is recognized as a comprehensive web-based LCA database, scientifically proved that Life Cycle Inventory Assessment metrics contained are highly correlated. A peer review process of the dataset is performed by an internal LCA expert before being accepted. The main assumptions considered are related to the inventory datasets and to the model formulation. The Ecoinvent 3.2 international industrial datasets provided are on a unit process and system process level. The unit process level datasets imply that inputs and outputs are recorded per production step, in addition to aggregated data sets (e.g., cradle-to-gate) (Finnveden et al., 2009).

Aside from other environmental tools, OpenLCA (GreenDelta GmbH, Berlin, Germany) was used because its code is open source, reducing the boundaries for the scientific community and the general public to perform LCA applications (Ciroth, 2007). OpenLCA is assumed to be a comprehensive tool that allows incorporation of location-specific characterization factors and uncertainty distributions (Hawkins et al., 2013). OpenLCA has been used in a wide range of applications worldwide since its release in 2007, i.e., agricultural sector (Ingwersen, 2012); distribution energy networks (Rodríguez et al., 2014) and power electronics (Braunwarth et al., 2015).

Fundamental uncertainties in this study could be due to uncertainties in the models configurations. Previous studies on emissions during construction stages found that geographic representativeness as one of the major source of uncertainty (Hong et al., 2016), as well as data quality and measurement assumptions at the origin production plants. The main influence of uncertainty on the results is the variation of several impacts due to technological correlation among production plants (energy mixes of manufacturing processes). This kind of uncertainty is defined and quality verified for each process by the Ecoinvent data quality guidelines (Weidema et al., 2013). According to these guidelines, the variance considered in each type of process emissions is 0.0006 for the demand of electricity and working material, and 0.12 for the combustion processes due to transport services. This study was performed considering these values of variance and a normal distribution.

Regarding the applicability of the model to a broader scenario, it requires assuming several hypotheses. These are: the rate of recycled steel scrap is 70%, the valorization of recycled concrete is not considered, and the energy mix for all the processes are equivalent to the following primary energy values considered: 21% of wind power, 6% of solar energy, 13% of natural gas, 19% of coal, 25% of nuclear energy, 2% of geothermal and 14% of hydraulic energy. Note that the electricity constantly varies (Gutiérrez et al., 2013), the electricity mix fluctuations are not currently reflected in the Ecoinvent dataset. Thus, the aforementioned values may be checked with the energy provider and updated in the model.

As regards the geographic boundaries of the impact categories, impact factors of acidification and eutrophication of ecosystems due to air pollutant releases have considered the data of average European effects, while the remaining impacts global warming, photochemical ozone formation and ozone depletion effects are considered globally. The temporal boundary considered in our system is 100 years. In this line, the method CML 2001 considers the global warming potential effects under the temporal scope of 100-year time.

A comparative analysis of earth-retaining walls has been performed from an environmental point of view. This analysis is carried out considering average values of the dataset and the variance suggested by the Ecoinvent data quality guidelines (Weidema et al., 2013). As for the uncertainties of the model, the assessments of the basic uncertainty factors of the data, including emissions measurements, are based in expert judgements. Table 1 shows the mean value, coefficient of variation and percentiles for each impact. Mean values are used as representative values for the following results.

2.2. Impact Categories

The impact categories considered are: the cumulative energy demand (CED), the global warming potential (GWP), the abiotic depletion potential (ADP), the acidification potential (AP), the eutrophication potential (EP), the ozone layer depletion potential (ODP) and the photochemical ozone creation (POCP). The POCP mostly defined by nitrogen oxides and volatile organic compounds (VOC), can be divided into two types: low photochemical ozone creation potential ($POCP_{low}$) and high photochemical ozone creation potential ($POCP_{high}$). $POCP_{low}$ generally occurs in rural areas and is mostly defined by NO_x levels while $POCP_{high}$ usually occurs in urban areas and in addition to the NO_x levels, this type also includes VOC contributions (Sillman et al., 1990).

2.3. Wall typology selection

The structural wall functionality of earth-retaining wall is based on the capability of the structure to sustain the terrain against the failure of a slope, but the type of structure will depend on the dimensions and location. The rock and the gabion walls are intended for earth-retaining purposes aims to withstand the terrain of a slope in road embankments. They are composed of rock blocks that work as gravity walls. Both use limestone as it is adequate to obtain equivalent sizes of the blocks and helps as natural filter so no drainage is needed apart from geotextile sheets. The gabion dam is specially used when the aesthetic of the site needs to be preserved so the availability of local stone is a criterion to consider. The reinforced concrete earth-retaining walls are used alongside a linear infrastructure, such as a road or railroad. This typology enables to build greater heights. The earth-retaining buttressed wall is characterized by its structural capacity to flexural moments. The buttresses are placed at some interval to tie the base slab and stem, and consequently reduce the shear force and bending moment. This type of wall usually leads to a more economical design. The buttressed wall is compared with another type of reinforced concrete wall (cantilever wall) and two types of stone walls for earth-retaining purposes (gabion and rock walls). A height of 7 m has been considered in the comparison. Fig. 1 shows the designs of these four types of earth-retaining walls. Their contribution flows to the impacts categories of CML 2001 are compared. Significant differences were found between the reinforced concrete walls and the stonework walls. Considering the buttressed wall as baseline for this comparison, the rate of contribution per midpoint impact is illustrated in Fig. 2.

As expected, gabion and rock walls show lower impacts than the RC walls. These types obtained less impact on ADP, AP, GWP, POCP, as the main flow contributors to such categories (cement and steel manufacturing) would be replaced by stone, with fewer burdens of burning processes. The impact results of the gabion and rock walls differ by large from the ones for the reinforced concrete earth-retaining walls. The choice for one or another type is based on the technical conditions or limitations. The applicability of gabion and rock walls as earth retaining structures is limited by the functionality, the structural performance to the typology and the height of the slope to retain. The results of the cantilever wall are not surprising either; this typology shows the highest impact share in all categories. This is due to the increment in the wall thickness to withstand the soil pressure, compared to the buttressed wall. This implies greater amount of carbon intensive materials for equivalent heights. As a conclusion, when the project restrictions prefer a reinforced concrete, the preference will be the buttressed wall provided there is no technical limitation in the backside. These project restrictions can require a high wall with reduced thickness or the impermeability of the wall.

2.4. Wall design

The analysis considers 30 different wall designs. Each design is the optimum cost solution. A hybrid harmony search heuristic optimization technique (García-Segura et al., 2015) is used to optimize the walls. The walls are distinguished by their heights (H) (Fig. 3), which range from 4–13 m (in 1 m increments), and by their permissible base soil stress which is 0.2 MPa for the first set of wall heights, 0.3 MPa for the second and 0.4 MPa for the third. Considering the concrete, 25 MPa grade is assumed with the following dosage: 250 kg/m³ of cement, 165 kg/m³ of water, 940 kg/m³ of gravel and 1050 kg/m³ of sand. The reinforcement steel used for all designs is B500S. It is because of the non-linear structural performance at different heights that different amounts of reinforcement and concrete are needed for each height. The structural compliance of the optimum walls is checked according to Spanish code (Fomento, 2008).

2.5. Functional unit

The definition of the functional unit includes two parameters. On the one hand, the height of the wall should be considered, as the ratio of reinforcement per volume of concrete increases at taller heights. On the other hand, the parameter of permissible strength is also relevant. The wall functionality is based on the capability of the reinforced structure to withstand the soil gravitating away from the stabilized soil. The soil permissible stress generally implies differential needs for stability (overturning and sliding). Thus, the functional unit of this linear infrastructure would be a linear meter of the installed wall for a specific height and permissible soil stress.

2.6. Life cycle model description

The life cycle of the wall is divided into five life stages as depicted in Fig. 4. The production stage includes all upstream activities that are necessary to obtain the respective construction material. For the concrete these will be activities including the excavation of the raw materials as well as their processing (e.g., crushing, grinding and mixing). Regarding the reinforcement steel bars of the concrete, the use of recycled steel is considered as meaning that two different steel productions streams are implemented. On the one hand, the production of new steel includes all processes from obtaining the raw materials at the quarry up to the melting in the so-called blast oxygen furnace (BOF). On the other hand, there is the production of recycled steel using an electric arc furnace (EAF), which takes into account steps such as collecting, separation and compacting of metal scrap. Ultimately, the steel production ends at the hot rolling facility where the rebar is formed. The final product considered within the production stage of the life cycle is the manufacturing of the plywood used as formwork for casting the concrete walls in-situ. Again, all upstream activities, from gathering the wood to cutting and forming the wood into panels, are included.

The transportation section of the life cycle includes the movement of materials from the respective plants to the installation site. These materials are: the plywood panels, the reinforcement rebar, and all concrete components (gravel, sand, water and Portland cement). Furthermore, the transportation of landfill material, namely the soil waste resulting from excavation during the installation, is regarded as well.

The installation phase includes all necessary activities to set up the wall at the designated site. These activities include: excavation with a hydraulic digger (as well as the partial refill with the same), mounting of the plywood formwork using a cordless screwdriver, and the compaction of the refilled soil using a vibrating tamper. After the installation the wall is considered to sustain a service life time of 100 years. During this stage only maintenance activities are expected; however, as sufficient durability constraints were imposed on the structures, maintenance activities are not considered. Hence, the service life time ends before an unacceptable concrete deterioration limit is reached, as previously suggested by García-Segura et al. (2014).

The final step in the life cycle of the retaining wall is the end of life stage. Here, activities such as digging up the refilled soil and the demolition of the wall are included. Activities considering the reuse of the remaining hole are not implemented, as the definition of any further use of the hole will belong to the next project. Therefore, it is unclear whether the hole would be refilled, reused or redesigned for a similar or alternative use. Nevertheless, the last step of recycling the steel is taken into account by transporting the wall remnants to a separation facility. Recycling of the concrete is not considered within this work, hence it will be going to landfill.

2.7. Model variables and parameters

The LCA-model is based upon several parameters. Table 2 and 3 summarizes the parameters common for all wall designs. Table 2 shows the general parameters, such as soil density, recycling rate, wood panel thickness, reusability of the panels, screwdriver time and transport distances. Table 3, however, shows the parameters associated with the measurements, which describe the usage of machinery for different processes in h/m³ and the weight related transportation of steel production in kg*km/kg steel. These parameters should be multiplied by the measurements of Table 4 to obtain the parameters per functional unit.

The majority of parameters are devoted to defining the transportations processes included in the LCA-model. There are two different types of transportation parameters: independently defined parameters (Table 2), given in km, which represent the transport distances of, for example, the steel reinforcement to the hot rolling facility and subsequently to the installation site or the transportation of soil waste to landfill; and parameters for the several material transportations taking place during the steel production (Table 3). Ecoinvent standard distances are used (Doka, 2003), given in kilograms per kilometer, and are linked to the cumulative amount of material consumed during the respective production step. Remaining transportation distances such as the movement of sand and gravel are automatically implemented in the respective LCA-process created by Ecoinvent.

Aside the aforementioned independent wall dimension parameters, there are parameters resulting from the optimized wall dimensions that describe the respective walls within the LCA-model. These parameters, which can be taken from Table 4, are: the total concrete volume (V_{con}) of the wall, the mass of the steel reinforcement (m_{st}), the volume of the soil waste (V_{sw}), the excavation volume of the hole (V_{exc}), the formwork area necessary to build the wall in-situ (A_{form}), and the refill volumes and resembling the refill volumes of soil on the heel (V_{heel}) and toe (V_{toe}) of the retaining wall. The refill volumes have been divided because the compaction of the refill soil on the heel (V_{heel}) is assumed to have an effort demand twice that of the one on the toe. These values are presented on a per functional unit basis (linear meter of wall).

3. Life cycle assessment results

Results are divided into seven contributing elements: the concrete production, the steel production, the transportation, the use of machinery for installation and demolition, the processing of landfill, and the formwork production.

3.1. Impact assessment categories

The influence of the wall height and permissible soil stress on the ADP (see Fig. 5), the AP (see Fig. 6), CED (see Fig. 7), the EP (see Fig. 8), the GWP (see Fig. 9), the ODP (see Fig. 10), the $POCP_{high}$ (see Fig. 11), and the low $POCP_{low}$ (see Fig. 12) is analyzed. The individual contribution of each element to each impact is represented. It is initially noticeable that all impacts follow a parabolic tendency with regard to the wall height. Fig. 5- 12 illustrate that fluctuation exists among the impacts concerning the permissible stresses between 11 and 13 m. This can be explained by the fact that these cost-optimized wall designs are comprised of varying material quantities. Furthermore, concrete is the worst contributor to every impact bar the ODP and the C. The machinery and transportation associated with ODP present similar values as concrete. The steel has a large impact for POCP, particularly in $POCP_{low}$ compared to $POCP_{high}$. In contrast to the concrete, the formwork is the least significant, as it not only exhibits the fewest contributions to each impact, but also has the lowest absolute impact increases between 4 and 13 m. Therefore, it is worth noting that the formwork has small environmental impact. Landfill presents a similar impact to that of formwork expect for EP and ODP.

Fig. 9 illustrates that for the GWP, concrete has the most significance influence compared to all other impact categories. From 4 to 13 m the concrete emissions for the 0.3 MPa series increase from 378 kg to 3587 kg of CO_2-eq. This represents an increase of 849.56%. Similarly, high growth rates can be identified for all impacts and elements. These impact increments are due to the increase in material amounts used for higher walls. Aside from the individual growth rates of every element it can be calculated that the POCP exhibits the highest overall increase, with increases up to 1106.5% for $POCP_{low}$ (0.2 MPa-13 m) and 9906.8% for $POCP_{high}$ (0.2 MPa-13 m). The high increase of the POCP could be related to the increased significance of steel as the wall height gets bigger. For example, the contribution of steel to the total $POCP_{low}$ for the case of the 0.2 MPa-series is 23.48% and increases to 46.8 %, thus being responsible for almost half the oxidation potential.

3.2. Contribution of each element

The contribution ranges of each element (concrete, landfill, machinery, formwork, steel, and transport) for each impact can be derived from Table 5 by averaging values for the three permissible stresses. In addition, indicators *I* and *D* denote whether the contribution share is increasing or decreasing, respectively, as the wall heights increase. Note that the concrete trend is not specified as there is not a clear contribution according to the wall height. That is to say that the concrete contribution to the total impact is similar regardless the wall height. Concrete almost always accounts for the largest contribution to each impact, except for the ODP where the use of machinery holds the biggest share (30.2% – 28.3%), and the POCP (both) where steel is the largest contributor at the bigger wall sizes. While concrete presents the smallest contribution in $POCP_{low}$ (20.5%), it contributes the highest for the GWP (60.2%).

When focusing on the landfill, a decrease for each impact category is identified. Landfill has the lowest impact on the GWP for the 13 m walls (with 3.4 %) and the biggest on the EP for the 4 m walls (with 14.7 %). Apart the significance of machinery on the ODP, this element is the second biggest contributor to various impacts including the CED, the AP, the GWP and the POCP (both). However, a decrease in percentage is registered for each impact category. An overall decreasing trend is also identified for the formworks contribution, which has most impact on the ADP, $POCP_{high}$ and $POCP_{low}$ of 4 m walls with percentages of 8.4%, 13% and 10.6%, respectively. Transportation has the most impact on the EP and ODP of the 13 m walls with 23.6% and 24.2%, respectively. Even though the impact of transport increases with higher walls, the relative contribution does not always increase. As for the steel, the contribution is lower than 17%, expect for the POCP (both), which increases the contribution up to 46.8%.

3.3. Influence of the wall height

In order to highlight the contribution of each element over the total impact with respect to wall height, a contribution ratio η_{ctr} will be used. This ratio is the relation between the percentage of contribution of a wall height and the percentage of contribution at a baseline of 4 m. These values are the average of the permissible soil stresses. Therefore, this ratio describes how the significance of each construction element changes as the wall height increases from 4 to 13 m. Using the GWP as an example, Fig. 13 shows that the steel doubles its contribution, whereas the contribution of the formwork material at least halves. Other impacts exhibit a similar trend. The contribution ratio for the formwork decreases for all impacts, depending on the impact at least to 0.81 for the EP and even down to 0.76 for the $POCP_{high}$. The steel contribution increases by factors ranging from 1.8 for $POCP_{low}$ to 2.28 for EP. The decrease in the contribution from machinery can be a rather small, from 0.94 for ODP to 0.78 for $POCP_{low}$. The landfill contribution ratio for 13 m presents values from 0.81 for EP to 0.65 for $POCP_{low}$. The transportation and the concrete always fluctuates around the ratio of η_{ctr}=1.

3.4. Impact factor

This section investigates the relationship of the impacts of concrete, steel and formwork with the amount of material used. An impact factor derived for each material and impact category is shown in Table 6. These values are multiplied by the amount of material used for each respective case to obtain the emissions or energy consumption for CED. It can be said that 1240 MJ per m^3 of concrete are consumed without considering pouring and mixing on-site, as these processes were considered in the machinery element. At the same time, 248 kg of CO^2-equivalent are emitted. The production of a kilogram of steel cumulates to an energy demand of 8.66 MJ and 0.843 kg of CO_2-eq. emissions. The kilogram ethylene-eq. emissions for $POCP_{high}$ and $POCP_{low}$ for the steel, where it is the main contributor, are 4.68E-4 and 5.65E-4, respectively. Likewise, it is worth noting that the impact factors of the formwork for energy demand are 42.4MJ and for the GWP are 2.67 kg of CO_2-eq.

3.5. Influence of steel recycling on the environmental impacts

In this section the steel recycling is studied. As stated in Table 2, 70% steel recycling was considered. Therefore, the impact factor per kilogram of steel shown in Table 7 corresponds to a percentage of recycling of 70%. As the results of the steel's impacts behave linearly it was also of interest to see what impact the steel recycling rate has on the results. For this purpose, another calculation was performed with openLCA with a recycling rate of 0% and 10% to see how the results change. The savings per 10 % recycling rate ($S_{10\%}$) were calculated using Equation (1). Note that $I_{0\%}$ and $I_{10\%}$ are the impacts with a recycling rate of 0% and 10%, respectively. Table 7 shows the results of $S_{10\%}$ for every impact category. The resulting emission or energy reduction when considering a 70% recycling rate ($R_{70\%}$) is evaluated according to Equation (2).

$$S_{10\%} = \frac{(I_{0\%} - I_{10\%})}{mst} \quad (1)$$

$$R_{70\%} = \frac{(I_{0\%} - I_{70\%})}{I_{0\%}} \quad (2)$$

These results show that the emissions of each impact category are reduced and the CED decreased as steel is recycled. When analyzing the calculated emissions per kilogram of steel depicted in Table 7, it is worth noting that the recycling rate influences each impact category by a different magnitude. The GWP factor of steel is reduced to 0.147 kg of CO_2-eq/kg steel when the recycling rate is 10%; however, the savings in other impacts are relatively different. Considering 70 % of steel was recycled within this model, huge emission and energy savings could be identified. The largest impact is observed on the depletion of abiotic resources with a saving of 72%. Also 57% of energy could be saved. Steel recycling is least impactful on the AP, but still a 70% recycling rate could cut the potential by 36%.

4. Conclusions

This study examines the LCA of 30 cost-optimized wall cases of 10 different heights (4 – 13 m) and different permissible soil stresses (0.2 MPa, 0.3 MPa, and 0.4 MPa). Results show that the impacts increase exponentially with the wall height, but the magnitude of each impact category increase varies due to differing contributions of the materials and upstream processes. Hence, the POCP increases most between 4 and 13 m by magnitudes up to 11.06 for the 0.2 MPa-series. This is due to the fact that the amount of steel used in greater wall sizes increases most compared to concrete or the formwork. In addition, the steel has a large influence on this impact category, as the results of the percentage contribution show. The considered permissible ground stresses appear to have small influence on the overall impacts as well as the individual processes' impacts.

In general, the significance of steel on every impact category is twice as high for the tallest walls. Thus, when trying to cut certain emissions, altering the steel amount within a project becomes more considerable as the wall sizes increase. Concrete also has a large contribution to all impact categories, due to the emission-intensive production of cement. Concrete has the largest impact on the GWP and contributes up to 60% of the total CO_2-eq. emissions. Reducing the amount of cement in concrete is often considered when aiming to reduce GWP. Thus, altering the concrete dosage is a widely acknowledged option. In contrast to the steel and concrete, the relative contributions of the other wall elements or processes, such as the machinery, the formwork, and the landfill, mostly decrease. The contribution of each element over the total impact varies with the wall heights. When increasing from 4 to 13 m, the steel doubles its contribution to the GWP, whereas the contribution of the formwork is halved.

This paper provides the impact factors per unit of concrete, steel and formwork. These values enable quick impact considerations during the design process. Furthermore, the impact reduction associated with the recycling rate of steel is studied. It is worth noting that using recycled steel greatly benefits the POCP. A steel recycling rate of 70 % was considered within this study, which reduced the contribution of steel to $POCP_{low}$ by 64 % as compared to no recycled steel. It is important to note that the results for each impact category present different influences on the recycling rate. While the AP is reduced by 36%, the same recycling rate (70%) provides a saving of 72% in ADP. The steel GWP factor is reduced in 0.147 kg of CO_2-eq/kg steel for each 10% recycling rate.

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List of Tables

Table 1. Contribution of a wall of 7 m. Mean value, coefficient of variation (CV) and percentiles (P)

Contribution of a wall of 7 m (per linear meter)

Midpoint impacts	Buttressed wall				Cantilever wall				Rock wall				Gabion wall			
	Mean	CV (%)	P_5	P_{95}	Mean	CV (%)	P_5	P_{95}	Mean	CV (%)	P_5	P_{95}	Mean	CV (%)	P_5	P_{95}
ADP (Kg Sb Eq)	6.23	5.3	5.75	6.75	12.44	5.2	11.40	13.49	6.20	6.1	5.58	6.84	5.58	4.7	5.13	6.01
AP (Kg SO_2 Eq)	4.53	5.29	4.15	4.95	8.88	5.89	8.05	9.71	3.90	6.25	3.51	4.30	3.52	5.45	3.198	3.837
CED (MJ Eq)	12410	4.41	11548	13388	24664	4.86	22740	26595	13692	6.11	12328	15117	12296	4.72	11314	13248
GWP (Kg CO_2 Eq)	1390	7.14	1233	1558	2821	7.57	2487	3178	892	6.05	803	983	806	4.55	744	866
EP (Kg NOx Eq)	5.39	4.62	5.00	5.81	10.36	5.27	9.51	11.23	5.98	6.32	5.37	6.60	5.36	5.71	4.838	5.867
$POCP_{high}$ (Kg ET Eq)	0.26	5.17	0.24	0.29	0.52	5.88	0.47	0.57	0.18	5.98	0.16	0.19	0.16	4.45	0.148	0.172
$POCP_{low}$ (Kg ET Eq)	0.22	5.53	0.20	0.24	0.45	6.26	0.41	0.50	0.15	5.94	0.13	0.16	0.13	4.31	0.125	0.144
ODP (Kg CFC-11 Eq)	1.22 E-04	3.73	1.15 E-04	1.30 E-04	2.42 E-04	4.14	2.26 E-04	2.58 E-04	1.61 E-04	6.09	1.45 E-04	1.78 E-04	1.45 E-04	4.66	1.33 E-04	1.56 E-04

Table 2. General parameters of the LCA

Parameter	Note	Value	Unit
Soil density		2680	kg/m³
Steel recycling rate		70	%
Thickness of plywood panels		0.05	m
Reusability of plywood panels		10	times
Cordless screwdriver		4	h
Transport of steel slabs (new & recycled) to hot rolling facility	Rail	80	km
	Lorry 16-32 t	20	km
Transport of steel from plant to installation site	Rail	80	km
	Lorry 16-32 t	20	km
Transport of cement from plant to installation site	Lorry 16-32 t	100	km
Transport of remnants from installation point to separation facility	Lorry 16-32 t	100	km

Table 3. Parameters of the LCA associated with measurements. Use of machinery and transport related to steel production.

Parameter	Note	Value	Unit	Values multiplied by
Uses of machinery: compaction				
Machineries with power >75 kW, diesel fueled	on toe	0.037	h/m³	V_{toe}
	on heel	0.074	h/m³	V_{heel}
Uses of machinery: mixing				
Concrete mixer (Power >75 kW, diesel fueled)		7.2	min/m³	V_{conc}
Uses of machinery: demolition				
Tired loader (Power> 75 kW, diesel fueled)		0.073	h/m³	V_{conc}
Compressor with jackhammers (Power>18.6 kW and <75 kW, diesel fueled)		0.36	h/m³	V_{conc}
Cutting equipment (Power>18.6 kW and <75 kW, diesel fueled)		0.4	h/m³	V_{conc}
Steel production: weight related transportation				
Raw materials to sinter facility	Lorry 16-32	0.57	kg*km/kg steel	m_{st}
	Rail	82.50	kg*km/kg steel	m_{st}
Raw materials to pellet facility	Lorry 16-32	0.43	kg*km/kg steel	m_{st}
	Rail	2.60	kg*km/kg steel	m_{st}
Raw materials to pig iron facility	Lorry 16-32	2.70	kg*km/kg steel	m_{st}
	Rail	67.77	kg*km/kg steel	m_{st}
Materials to Iron Scrap preparation facility	Lorry 16-32	84.09	kg*km/kg steel	m_{st}
	Rail	168.18	kg*km/kg steel	m_{st}
Materials to EAF facility	Lorry 16-32	83.30	kg*km/kg steel	m_{st}
	Rail	84.70	kg*km/kg steel	m_{st}
Materials to BOF facility	Lorry 16-32	6.90	kg*km/kg steel	m_{st}
	Rail	43.20	kg*km/kg steel	m_{st}

Table 4. Measurements of the analyzed wall designs per linear meter of wall

Soil stress (MPa)	Wall height (m)	V_{con} (m^3)	m_{st} (kg)	V_{sw} (m^3)	V_{exc} (m^3)	A_{form} (m^2)	V_{heel} (m^3)	V_{toe} (m^3)
0.2	**4**	1.545	37.672	2.640	6.602	9.381	3.319	0.644
	5	1.961	57.681	3.220	8.217	12.019	4.420	0.578
	6	2.480	90.779	4.040	10.291	14.889	5.447	0.804
	7	3.334	148.050	5.680	13.181	18.337	6.595	0.906

	8	4.781	220.503	7.800	16.757	22.078	7.684	1.273
	9	5.438	323.476	9.500	20.118	26.089	8.935	1.683
	10	7.206	429.339	11.700	24.128	30.648	10.107	2.321
	11	9.006	474.076	12.880	26.151	36.187	11.252	2.019
	12	10.867	617.791	14.080	28.249	37.967	12.374	1.795
	13	14.510	905.976	17.740	34.875	43.452	13.656	3.480
0.3	**4**	1.524	44.364	2.740	6.966	9.196	3.319	0.908
	5	1.953	60.809	3.240	8.325	11.926	4.408	0.677
	6	2.482	88.735	3.780	9.723	14.700	5.481	0.462
	7	3.274	133.948	5.120	12.072	18.057	6.564	0.388
	8	4.393	216.737	6.760	14.928	21.491	7.653	0.515
	9	5.355	296.535	8.380	17.974	25.726	8.840	0.754
	10	7.682	405.562	10.140	21.068	28.034	9.878	1.050
	11	10.004	598.411	14.020	27.753	33.788	11.027	2.706
	12	10.867	617.791	14.080	28.249	37.967	12.374	1.795
	13	14.456	744.409	15.580	31.142	41.308	13.450	2.113
0.4	**4**	1.534	36.277	2.640	6.604	9.418	3.353	0.611
	5	1.979	52.478	3.180	7.988	12.223	4.445	0.363
	6	2.470	82.479	3.880	9.744	14.907	5.506	0.359
	7	3.227	126.897	5.020	11.906	18.037	6.574	0.312
	8	4.656	179.422	6.620	14.577	21.729	7.570	0.386
	9	5.344	256.337	7.840	16.923	25.378	8.775	0.308
	10	7.743	356.662	9.240	19.422	27.848	9.828	0.354
	11	8.177	456.250	10.740	22.337	33.554	11.242	0.355
	12	11.290	598.365	13.080	26.170	35.713	11.993	1.098
	13	13.579	670.817	14.220	28.844	40.397	13.405	1.219

Table 5. The percentage contribution of each element for every impact, including a trend indicator decrement (D) or increment (I) of the progression over the wall height.

	Concrete			**Landfill**			**Machinery**			**Formwork**			**Steel**			**Transport**		
	Min	**Max**		**Min**	**Max**		**Min**	**Max**		**Min**	**Max**		**Min**	**Max**		**Min**	**Max**	
ADP	39.9	43.5	~	7.9	10.4	D	15.1	17.1	D	4.0	8.4	D	4.8	12.6	I	17.2	18.5	I
AP	34.2	37.0	~	5.3	7.2	D	20.9	23.6	D	3.4	7.4	D	6.4	16.2	I	17.9	19.1	I
CED	31.6	34.2	~	5.7	7.7	D	23.1	25.8	D	3.3	7.1	D	5.6	14.4	I	19.4	20.8	I
GWP	56.5	60.2	~	3.4	4.7	D	13.4	15.2	D	1.8	4.0	D	4.8	12.2	I	11.0	11.4	I
EP	34.3	37.5	~	11.5	14.7	D	18.0	19.8	D	3.6	7.3	D	2.3	6.4	I	21.3	23.6	I
$POCP_{high}$	28.5	34.4	~	6.0	8.6	D	13.0	16.5	D	5.4	13	D	15.5	35.1	I	10.4	12.0	D
$POCP_{low}$	20.5	27.1	~	7.2	11.5	D	11.9	16.7	D	4.0	10.6	D	22.9	46.8	I	8.8	11.2	I
ODP	26.4	28.5	~	6.7	8.9	D	28.0	30.3	D	3.0	6.3	D	4.1	10.8	I	22.6	24.2	I

Table 6. Impact factors per unit of concrete, steel and formwork

	Concrete (~/m^3)		**Steel (~/kg$_{st}$)**		**Formwork (~/m^2)**	
	Amount	**Unit**	**Amount**	**Unit**	**Amount**	**Unit**
ADP	5.71E-01	kg Sb-Eq	2.75E-03	kg Sb-Eq	1.85E-02	kg Sb-Eq
AP	6.65E-01	kg SO_2-Eq	4.87E-03	kg SO_2-Eq	2.15E-02	kg SO_2-Eq
CED	1.24E+03	MJ-Eq	8.66E+00	MJ-Eq	4.24E+01	MJ-Eq
GWP	2.48E+02	kg CO_2-Eq	8.43E-01	kg CO_2-Eq	2.67E+00	kg CO_2-Eq
EP	6.00E-01	kg NOx -Eq	1.69E-03	kg NOx -Eq	2.02E-02	kg NOx -Eq
$POCP_{high}$	2.46E-02	kg C_2H_4-Eq	4.68E-04	kg C_2H_4-Eq	1.51E-03	kg C_2H_4-Eq
$POCP_{low}$	1.58E-02	kg C_2H_4-Eq	5.65E-04	kg C_2H_4-Eq	1.01E-03	kg C_2H_4-Eq
ODP	1.02E-05	kg CFC-11-Eq	6.45E-08	kg CFC-11-Eq	3.79E-07	kg CFC-11-Eq

Table 7. Impact savings per 10 % of steel recycling rate and impact reduction in steel due to a 70 % recycling rate

	ADP	**AP**	**CED**	**GWP**	**EP**	**$\mathbf{POCP_{High}}$**	**$\mathbf{POCP_{Low}}$**	**ODP**
Unit	kg Sb-Eq	kg SO_2-Eq	MJ-Eq	kg CO_2-Eq	kg NOx-Eq	kg C_2H_4-Eq	kg C_2H_4-Eq	kg CFC-11-Eq
$S_{10\%}$ **(~/kg_{st})**	1.03 E-03	3.95 E-04	1.64	1.47 E-01	1.74 E-04	1.10 E-04	1.43 E-04	7.77 E-09
$R_{70\%}$ **(%)**	72%	36%	57%	55%	42%	62%	64%	46%

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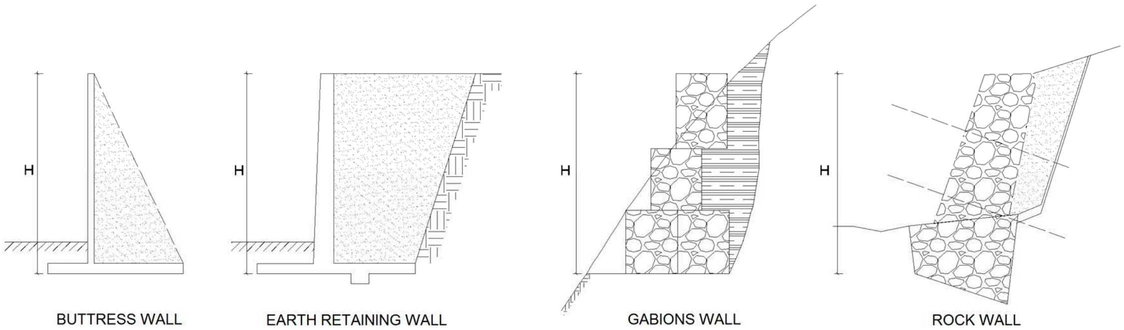

Fig. 1. Earth-retaining wall designs

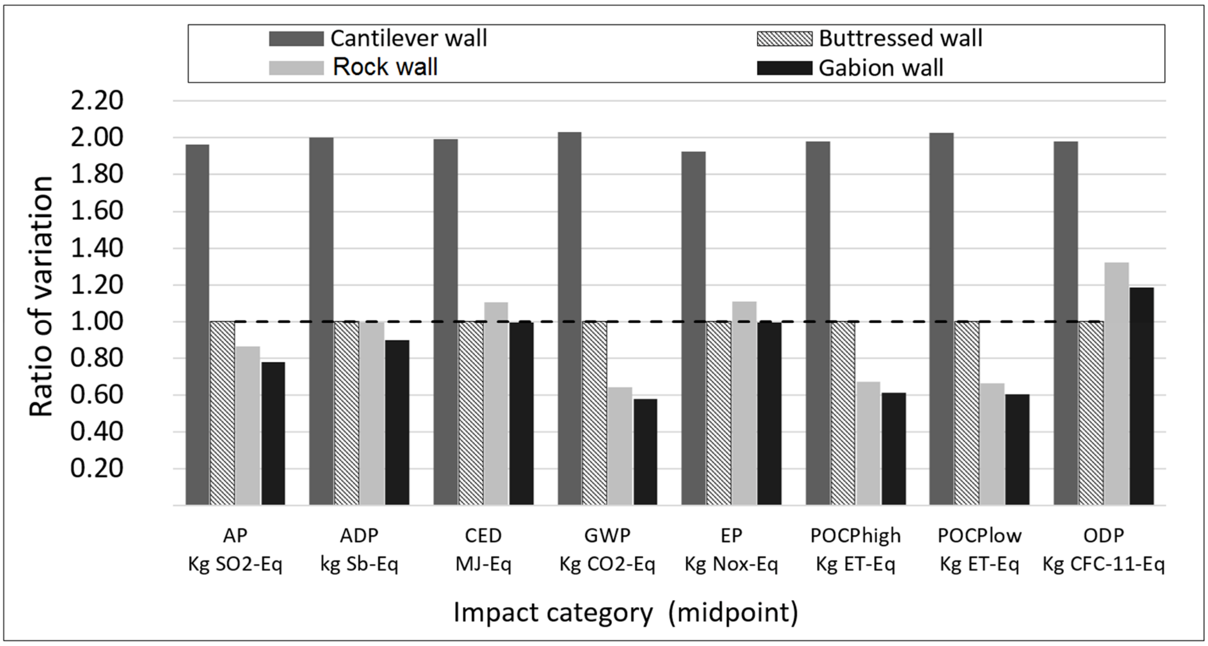

Fig. 2. Variation of impacts per wall typology compared to the buttressed wall

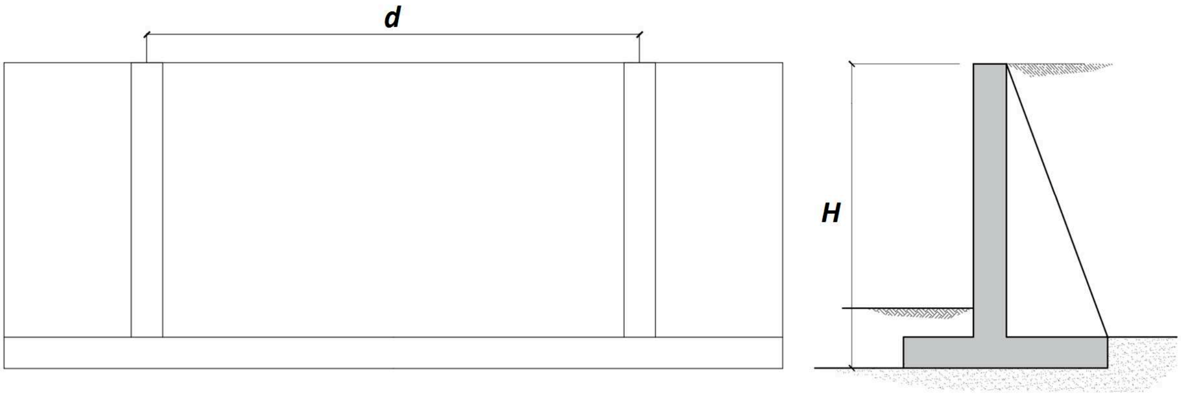

Fig. 3. Dimensions of the earth-retaining wall

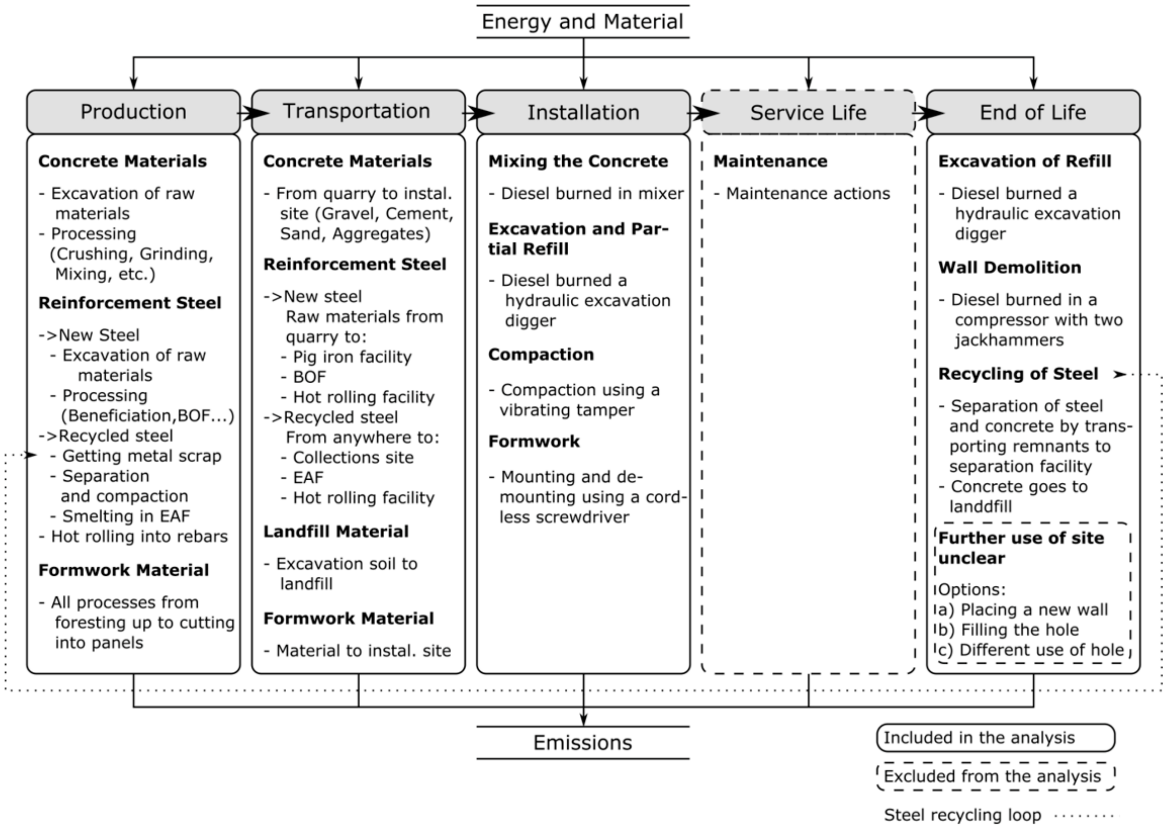

Fig. 4. Life cycle of the earth-retaining wall divided into stages

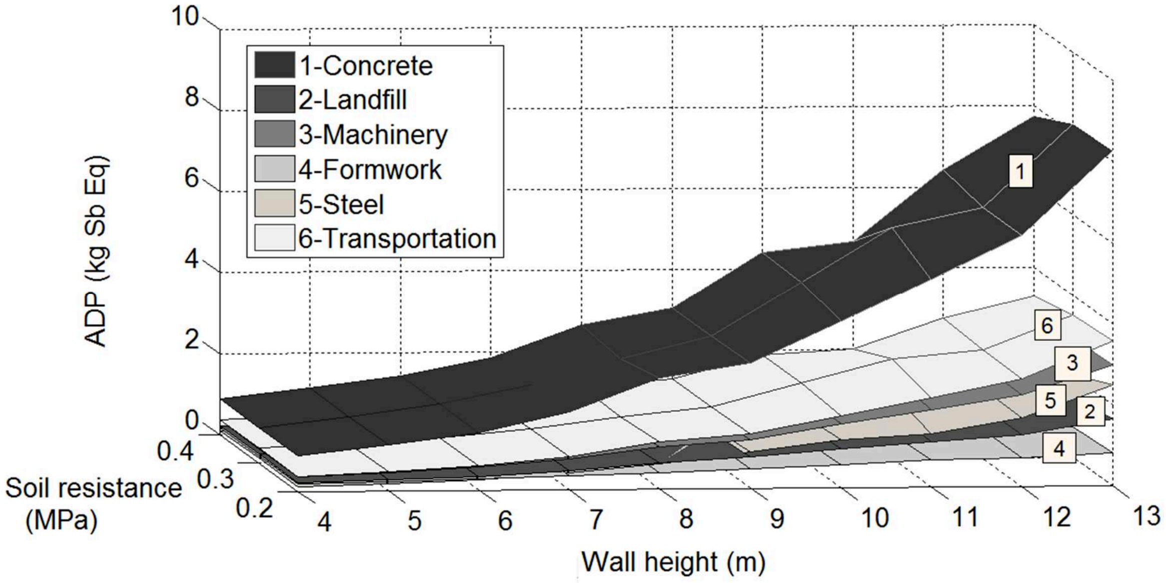

Fig. 5. Development of the ADP with regard to wall height and permissible soil stress

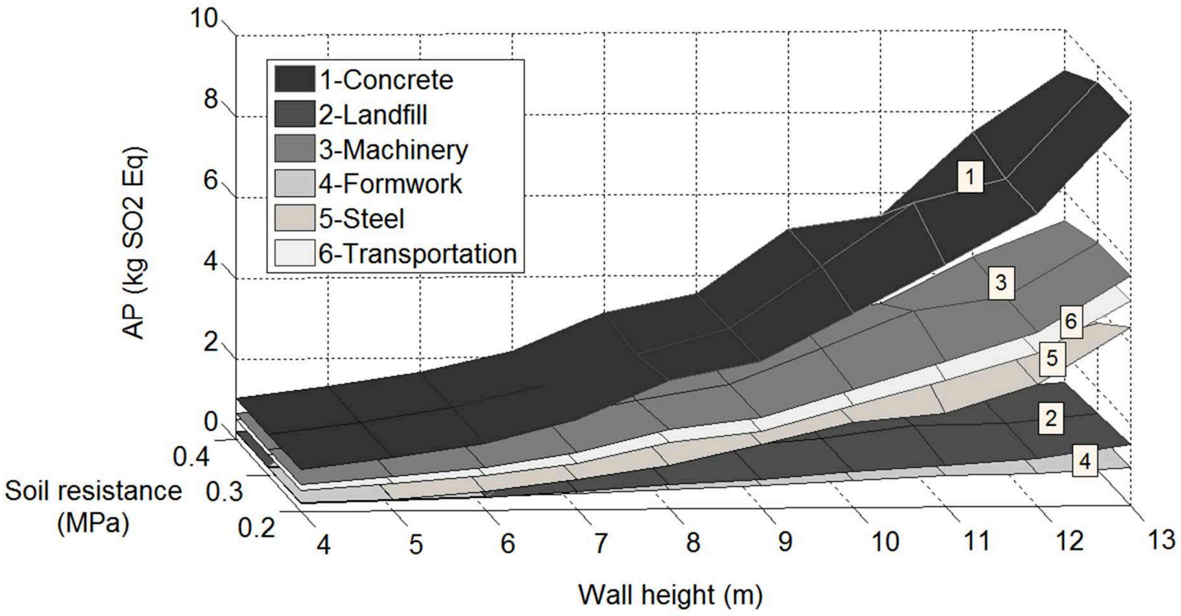

Fig. 6. Development of the AP with regard to wall height and permissible soil stress

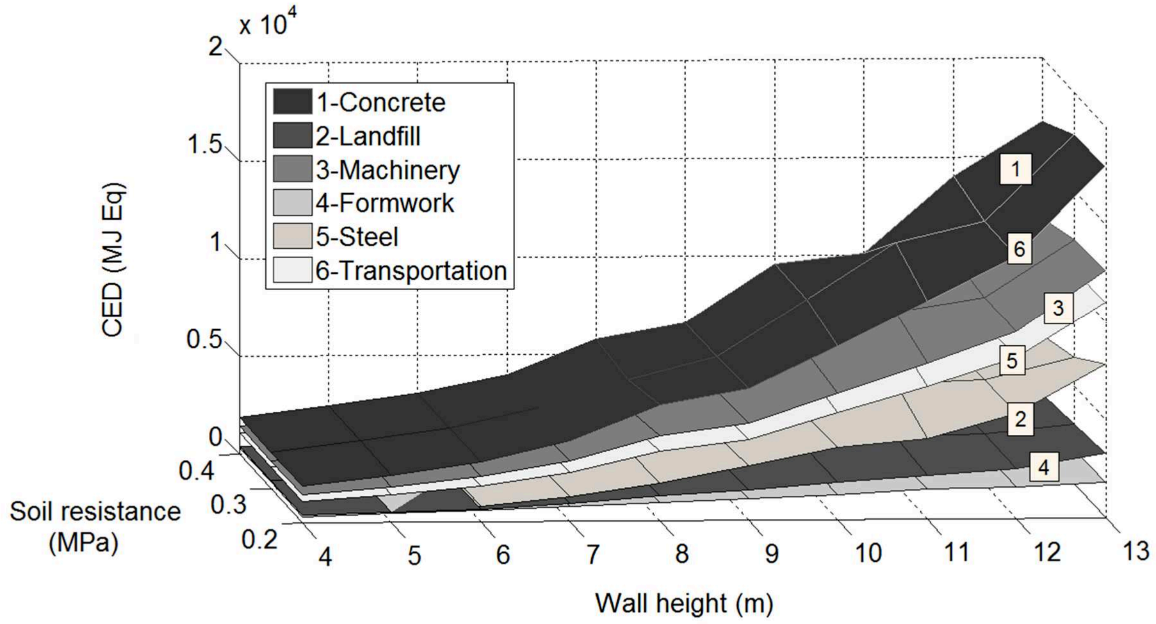

Fig. 7. Development of the cumulated energy demand with regard to wall height and permissible soil stress

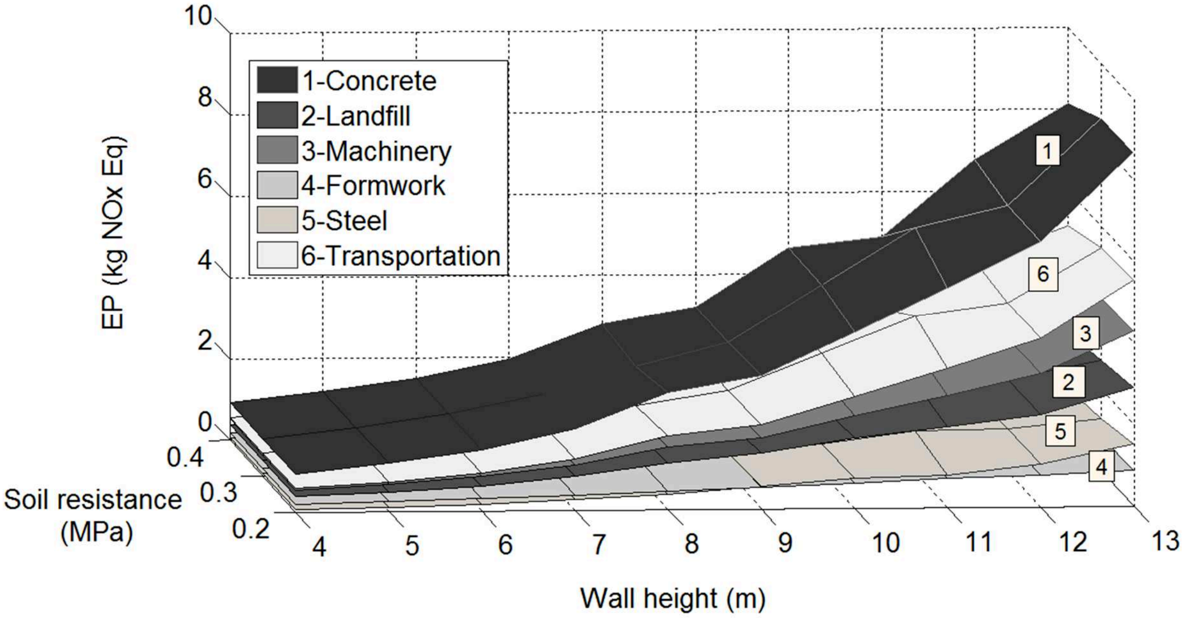

Fig. 8. Development of the EP with regard to wall height and permissible soil stress

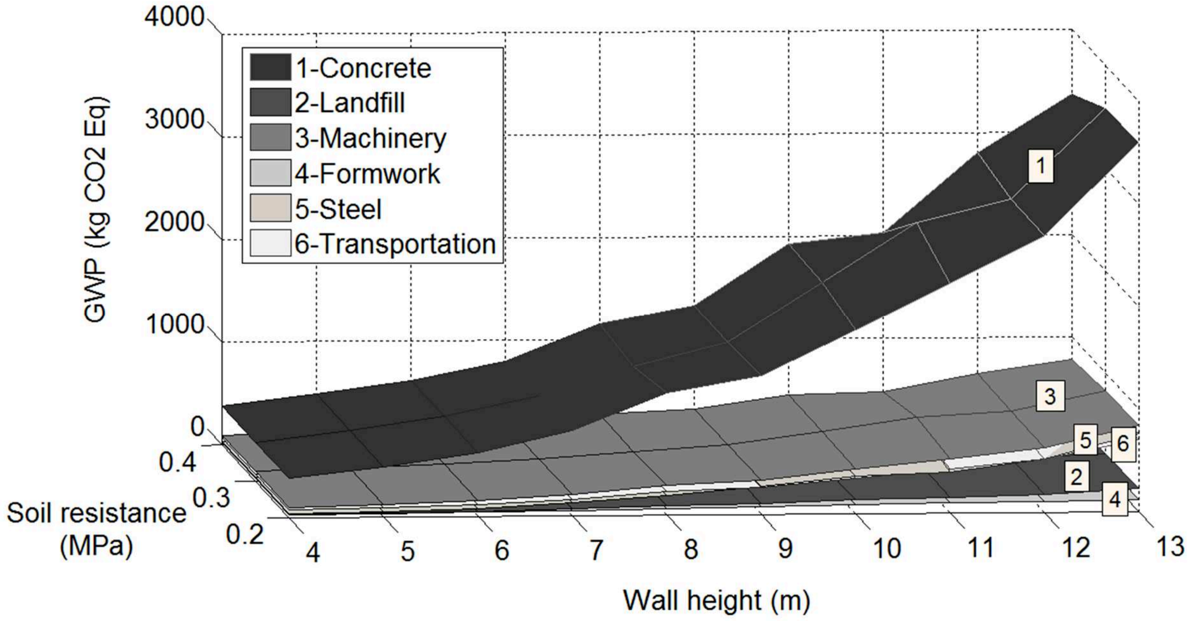

Fig. 9. Development of the GWP with regard to wall height and permissible soil stress

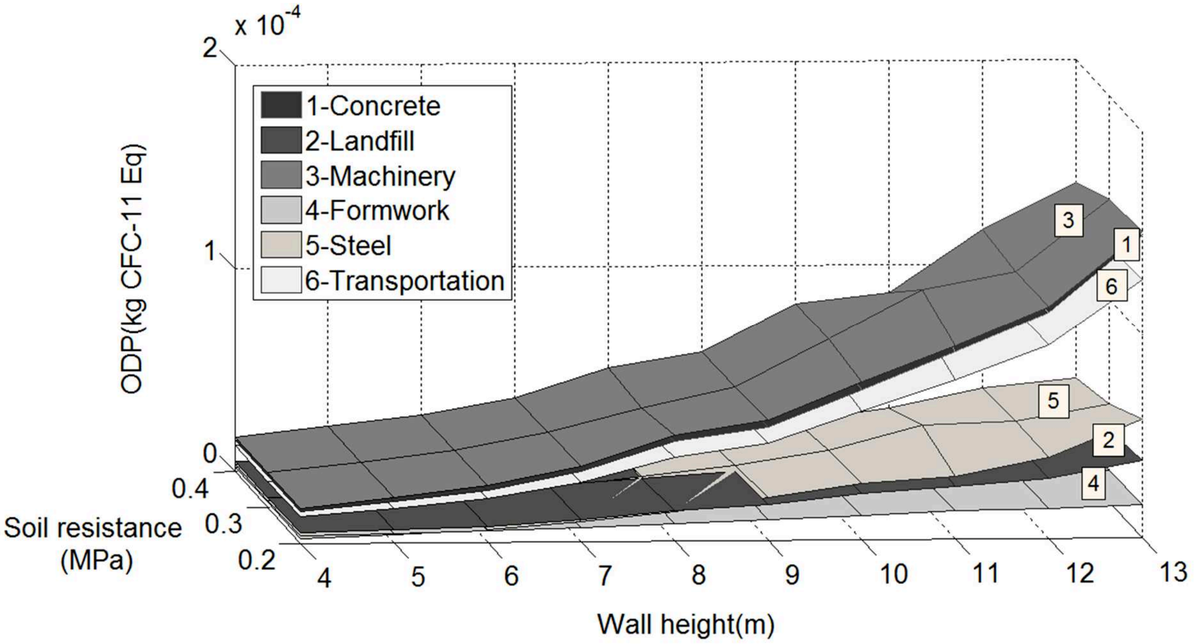

Fig. 10. Development of the ODP with regard to wall height and permissible soil stress

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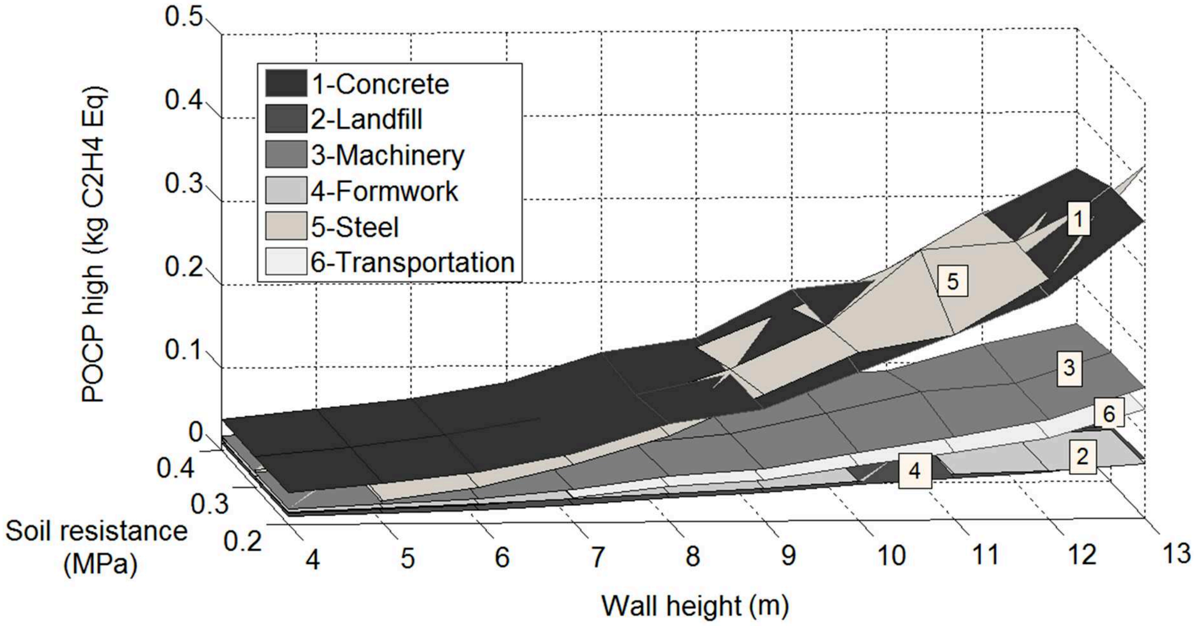

Fig. 11. Development of the $POCP_{high}$ with regard to wall height and permissible soil stress

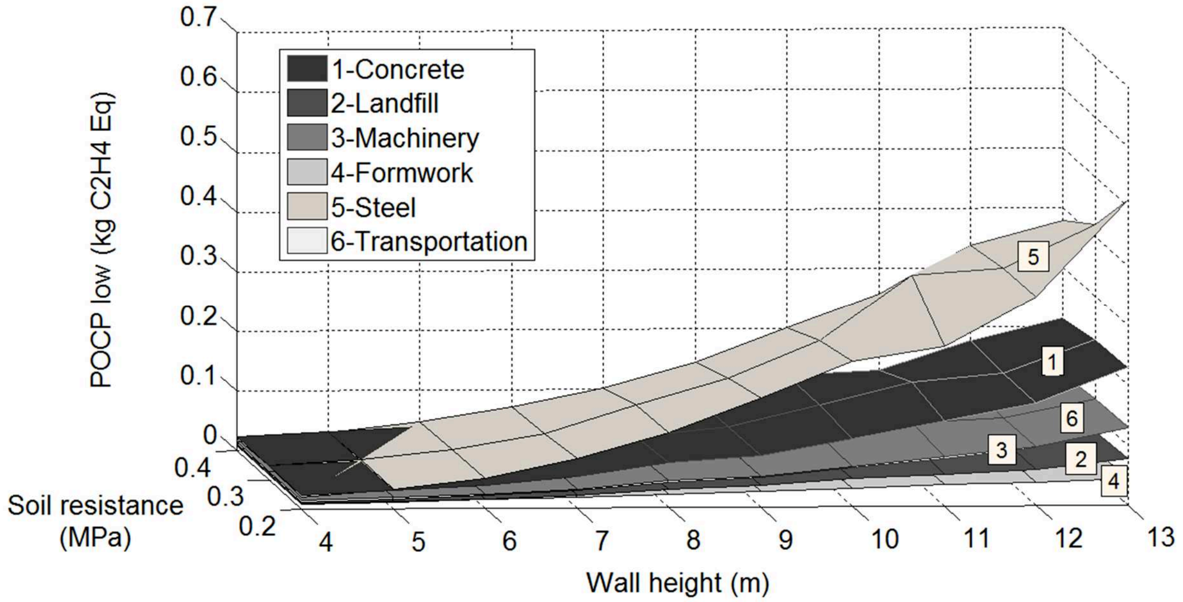

Fig. 12. Development of the POCP$_{low}$ with regard to wall height and permissible soil stress

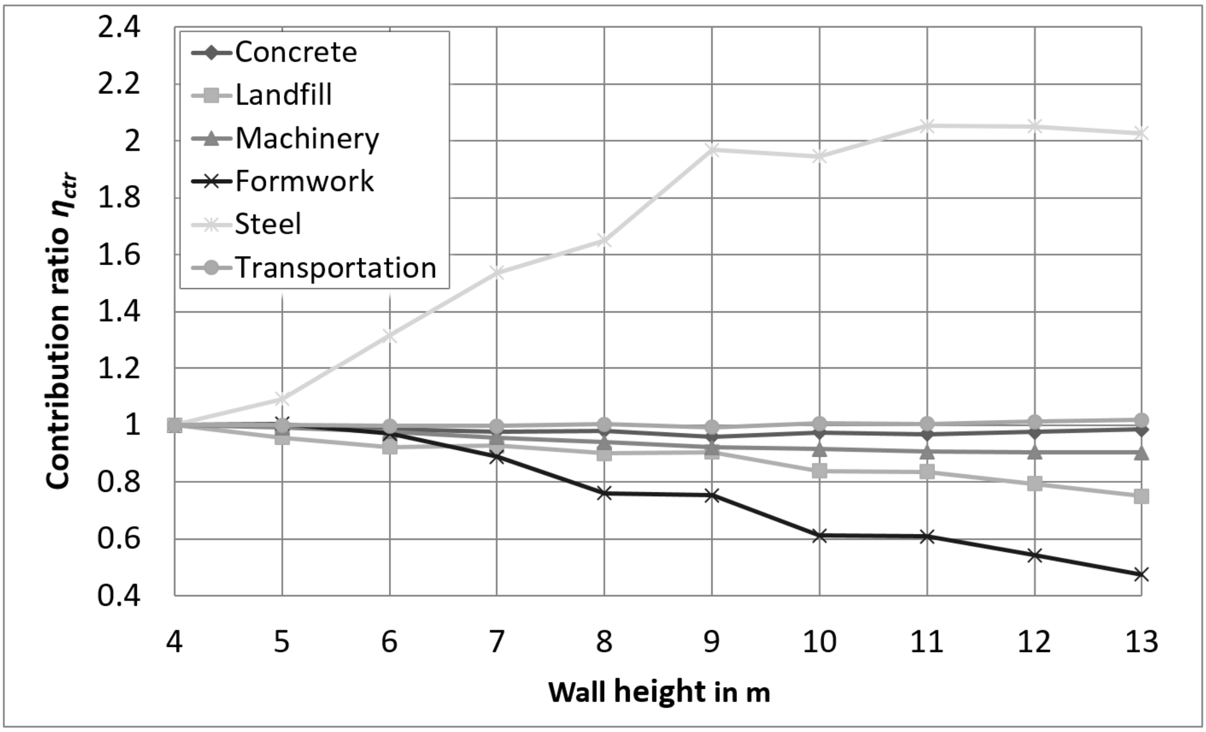

Fig. 13. Development of the contribution ratio of every element over the GWP according to wall height.