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A plant based LCA of high-strength prestressed concrete elements and the assessment of a practical ecological variant

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ABSTRACT

In the context of the rising awareness regarding sustainability, a Belgian producer of high-strength prestressed concrete elements for structural and civil applications aimed to clarify several aspects of ecological certifications and standards, and the application of these items within the company. In a first part of this paper, a life cycle assessment (LCA) for the precast element production up to delivery on site is presented, in which accurate company information and specific data from internal and external databases is used. The LCA determines that although reinforcing steel and cement dominate the impact contributions, other factors such as transport by road, maintenance, aggregates, element fabrication and concrete waste are non-negligible. Subsequently, a study of an ecological variant, presented in the second part of this paper, shows that several adaptions within the manufacturing process can potentially reduce the impact on the environment with 20–30%, depending on the assessment method used.

1. Introduction

In general, the construction industry unfortunately is among the largest consumers of materials and energy, and it is a significant polluter [1]. Especially concrete, the world's second most consumed material after water [2], contributes to this pollution, since every year about 25 billion tonnes of concrete are produced worldwide [3].

Within concrete as a material, cement is an essential component, and is applied in large amounts as well. In 2014 the global production of cement was 4.3 billion tonnes [4]. The production of one tonne of cement requires about 1.5 tonnes of raw material and about 4000–7500 MJ of energy. Additionally, each tonne of cement involves the emission of approximately one tonne of CO_2 [5]. For typical normal strength concrete mixes using Portland cement as the only binder, the Portland cement is found to be the primary source of CO_2 emissions, being responsible for 74%–81% of total CO_2 emissions for concrete production. Subsequently coarse aggregates are the next major source of CO_2 emissions, contributing to 13%–20% of the total CO_2 emissions [6].

This environmental impact of concrete has become an important issue in the industrial world for the reason that many major infrastructure owners require environmentally sustainable designs, and many customers consider different ecological options with a critical view. As a response, more and more product manufacturers using concrete as raw material provide environmental product declarations (EPDs) and develop the capabilities necessary to manage sustainability [7]. In this respect, it is clear that the various branches in the construction sector are concerned about the environmental impact of their activities.

This is the case for a Belgian producer of high-strength prestressed concrete elements for structural and civil applications, for whom in this paper a life cycle assessment (LCA) study is presented. The LCA evaluates the possible environmental footprint and the applied resources in the company, starting from the raw materials, over the production and use phase, up to the waste and recycling phases [8]. The choice for the LCA method derives from the fact that

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LCA is recognized as an innovative methodology which improves sustainability throughout all stages of a products life cycle. It has a broad international acceptance as a means to improve environmental processes and services [9]. The introduction of LCA in the construction industry is of significant importance since the system is capable of measuring each ecological impact systematically and objectively [10]. Although, next to LCA, there are several other interesting options such as parametric associative models [11] or eco-cost/value models [12,13], these models seem not yet sufficiently developed to assess sustainability.

Many recent LCA studies regarding the construction industry have focused on the maintenance and operational phases of construction projects, since these phases generally account for the largest part of the energy consumption during the life cycle of buildings. However, the production phase, transportation and onsite construction should not be disregarded. At least one study which investigated the production, transportation and construction phases concluded that the production stage has the largest amount of energy consumption and greenhouse gas (GHG) emissions [14]. This is, next to the large interest of the industry, also a reason why in this paper we take a closer look at the production phase of concrete elements. Next to this, due to new regulations, new buildings become more energy efficient, and thereby the environmental burdens of the operation phase, for example due to heating and/or cooling, decrease significantly. In this way the other phases of the life cycle gain in importance, e.g., choice of materials, construction, end-of-life and water use [15].

As mentioned above, in a first part of the presented study the activities of a specific manufacturer of high-strength prestressed concrete elements were scrutinized. For this, a life cycle analysis based on an average production of the company over one year is performed. To develop this LCA, the data were applied in a cradle to gate approach in which also the maintenance, waste and recycling phases are incorporated. This approach is further in this study referred to as a cradle to gate approach “with options”. Next to this first part, several options to produce more sustainable high strength prestressed concrete elements in this specific case study were assessed in the LCA, yet maintaining the standards of for example NBN EN 206 as applicable for concrete. In a third part, a comparison was made between the three main types of structural elements constructed in the company based on their load bearing capacity and material content. During the research, attention was paid to the interaction between the concrete strength, durability and sustainability, and the use of several standards in Belgium and Europe.

2. Research relevance

The three parts of the study mentioned in the introduction section constitute together an interesting and specific application of LCA in the construction sector. Its added value to the existing literature on LCA of concrete mainly lies in the fact that the analyses have been conducted in close collaboration with industry. Unlike other more theoretical LCA studies in this research field, the calculations in this paper are based on reliable first-hand inventory data regarding the actual operation of a precast concrete plant and the typical concrete products produced by it. In addition, the study represents a realistic strategy towards a higher sustainability because it accounts for all limitations imposed by the applicable regulations and standards on a European level as well as other practical circumstances of the specific Belgian national context.

Furthermore, the paper can serve as an example for future studies: several choices that have to be made when performing an LCA can be based on the choices made in this study, while the input data used in this study as well as the output results can be used to fill data gaps. Next to this, the paper presents a clear example of how a producer of prefabricated concrete elements is structured, which can be used in for example the development of product category rules (PCRs).

Moreover, insight is provided into the fact that the material ‘concrete’ does not have only one environmental impact score. In contrast, the environmental burden depends on the concrete mixture, the type of concrete element and the specific situation such as the need for a load bearing capacity. In addition, the paper identifies potential improvements for the environmental impact and which changes will have the greatest effect.

3. Research approach

The ISO_14040 standards prescribe how to create each LCA in four steps: the definition of the goal and scope, the life cycle inventory, the life cycle impact assessment, and the interpretation [8,16]. Since these standards offer useful guidelines to compose an LCA, they are applied in this study. In the following the goal and scope of this particular study are clarified.

3.1. Goal

In this context, the goal of the study is to present a specific example of the application of LCA in the concrete industry. For this, the goal is divided into three parts. First, an analysis of the current processes in the concrete company has to be executed. Subsequently, a more ecological version of these current processes has been based on previous findings in literature. This ecological version is composed and analyzed in reference to the traditional way of working in the concrete company. In this, it has to be determined which factors are important and which are less relevant. Thirdly, a comparison has to be made between the three structural elements in the concrete company: beams, TT-elements and floor slabs. The comparison is analyzed according to the load bearing capacity of each element and their material content.

3.2. Scope

The definition of the scope is very important, since in the scope all boundary conditions of the LCA are defined. In this way, the comparability of different LCA's depends on their respective scope definitions. This comparability is of great importance, because the results of an LCA are not directly intended to be used individually, but become more interesting when they can be compared with LCA results for similar subjects [15,17]. This is the reason why, for this specific study, the life cycle assessments of the traditional concrete production and the ecological version are developed according to the same scope definition. For the whole analysis, the SimaPro7 software package and the Ecoinvent 2.0 database [18] were used. In the following paragraphs the scope will be defined according to the functional unit, system boundaries, allocation principles and the life cycle impact assessment methodologies.

The functional unit is seen as the reference unit of the product system for which the environmental impact will be calculated. In the building industry different functional units can be interesting, such as a certain surface area or a predefined volume of the product under study, an element providing the defined load bearing capacity, the occupancy, …In this study, the functional unit had to correspond to the overall production of the concrete company with the possibility to evaluate the relative impacts of the different contributing processes. Next to this, the assumed service life can influence the results, so it was desirable to incorporate the service life for which the company mostly calculates the concrete elements. For these reasons, the functional unit was set to be one m^3 of finished concrete product with a service life of 50 years.

The boundaries of the system correspond to the mentioned cradle to gate approach with options. Not only the raw materials for the composition of the concrete, the transport and fabrication are included, but also the maintenance of the finished concrete structure, disposal and recycling. As is mentioned in Van den Heede et al. [19] this system boundary is indeed advised when comparing different concrete compositions. The decision to not further extend the boundaries to more “other options” or to a cradle-to-cradle approach, is based on the fact that this wouldn't correspond to the possibilities and activities of the co-operating company, and more in general to the precast concrete industry.

The ISO_14040 standards advise to avoid allocation. In general, allocation is defined as partitioning the input or output flows of a process or the product system between the product system under investigation and one or more other product systems [8]. Where avoidance was impossible in the system, allocation was considered accurately. The concrete mixtures (five in total), the reinforcement bars and strands and their respective ecological variant, were all developed in the system as a process with a valuable output and a waste output. Environmental impacts were allocated to these two outputs on a mass basis. In contrast, for the outputs in the process of cement replacing materials allocation was done on an economical basis. As is extensively explained in Van den Heede et al. [19], the allocation of industrial by-products, like fly ash, is a complicated matter. The decision of the economical allocation here is based on the fact that economical allocation imposes less environmental impacts to the industrial by-products than mass allocation, which may encourage the concrete industry more to continue using by-products as partial cement replacement. The last process where allocation had to be applied, is the process of cleaning the concrete mixers. This cleaning process results in two outputs: the cleaning water and the concrete sludge. The assumption is made that an allocation of 20% for the cleaning water and 80% for the sludge is acceptable, because the concrete sludge will be much more damaging to the environment in comparison to the cleaning water.

Lastly, in the scope definition the life cycle impact assessment (LCIA) methodology and the types of impacts have to be defined. In this study the decision has been made to evaluate the results of the life cycle inventory (LCI) with both a midpoint (problem oriented) and an endpoint (damage oriented) impact assessment method, to get a more complete picture of the results. The two assessment methods adopted are respectively EPD 2008 [20] and Eco-indicator 99 [21].

4. Life cycle inventory

4.1. Traditional production

The data used for the life cycle inventory are chosen as accurate as possible, based on the high importance of the data used for the accuracy of the results in a life cycle assessment, as is stressed in Gursel et al. [22]. A flow diagram (Fig. 1) of the production in the company was made in order to get an overview of the different processes and flows. Out of this diagram, inventory details were collected along with their interrelationships. Several details and figures were provided and were used for the input in the LCA software. The different relations between the numerous processes were respected according to the given information, and for more specific data about input and output quantities was relied on the Ecoinvent database. Here, the processes were as much as possible chosen with a reference to Belgium or Europe.

4.1.1. Processes

The basis of the life cycle inventory is the build-up of the processes. A short enumeration of the different types of processes used is given in Table 1. The processes of the different raw materials for the concrete mixtures occurring in the production chain of the company were firstly developed in SimaPro. For these, the best fitting processes in the Ecoinvent database according to the given data about the raw materials, were combined with the distances from the company to the different suppliers and the according transport medium. In this way, it was possible to compose in SimaPro each raw material-process of the specific company, based on a process of the Ecoinvent database combined with the transport to the concrete company.

Out of these raw material processes, the different concrete mixtures could then be composed. In the company, five different mixtures are used, these can be found in Table 2. The main raw materials of an average concrete composition are coarse and fine aggregates, cement and water, and often some additions.

Two reinforcement processes occur within the production chain of the company. There is a process for steel bars and a process for prestressing steel strands. Both are built up in an analogue manner as the raw materials, so the transport from the supplier to the concrete company is also accounted for.

The supply of materials to the company is done by four different types of transport: transport by lorry (EURO 5), by barge, by ocean bulk carrier and by ocean container ship. The values given in Table 1 for the transport to the company of raw materials should be seen with a critical view. For all raw materials used in the LCA, except one, the maximum occurring transport by road is 200 tkm and by ship 100 tkm. For many raw materials these transport distances are even much smaller. Only one kind of coarse aggregates has a transport of 1800 tkm by bulk carrier over the ocean. The other basic processes, cleaning water, working hours and energy, are all based on information of the specific company. The processes were developed according to information in the Ecoinvent database, and have been adapted to reflect the actual data better.

4.1.2. Assemblies

Based on the various processes, the assemblies are composed in the SimaPro7 software, according to the data associated with the company. For each assembly there are three versions, one for each type of structure manufactured in the concrete company (beams, TT-elements and floor slabs). The different assemblies are listed in Table 3. In each case, the different basic assemblies are combined to compose the matching finished product assembly of the beams, the TT-elements or the floor slabs. All these finished product assemblies in turn are composed to form the total production assembly of the company.

The different output quantities reflect the actual numbers occurring in the production chain of the company, or result from the earlier processes. Of course, sometimes there are differences between the assemblies of the beams, TT-elements and floor slabs. Mostly these differences are a result of different dimensions or material use. Next to this, for the production of floors, additional energy is required for heating, and in these elements only prestressing steel strands are used.

The company uses reusable steel formwork. The service life of the formwork elements can be considered infinite, since in practice the formwork never has to be replaced. In this way, the formwork elements themselves do not have to be incorporated in the life cycle assessment. Thus the traditional use of formwork consists in this LCA only of an amount of non-recycled polystyrene and lubricating oil.

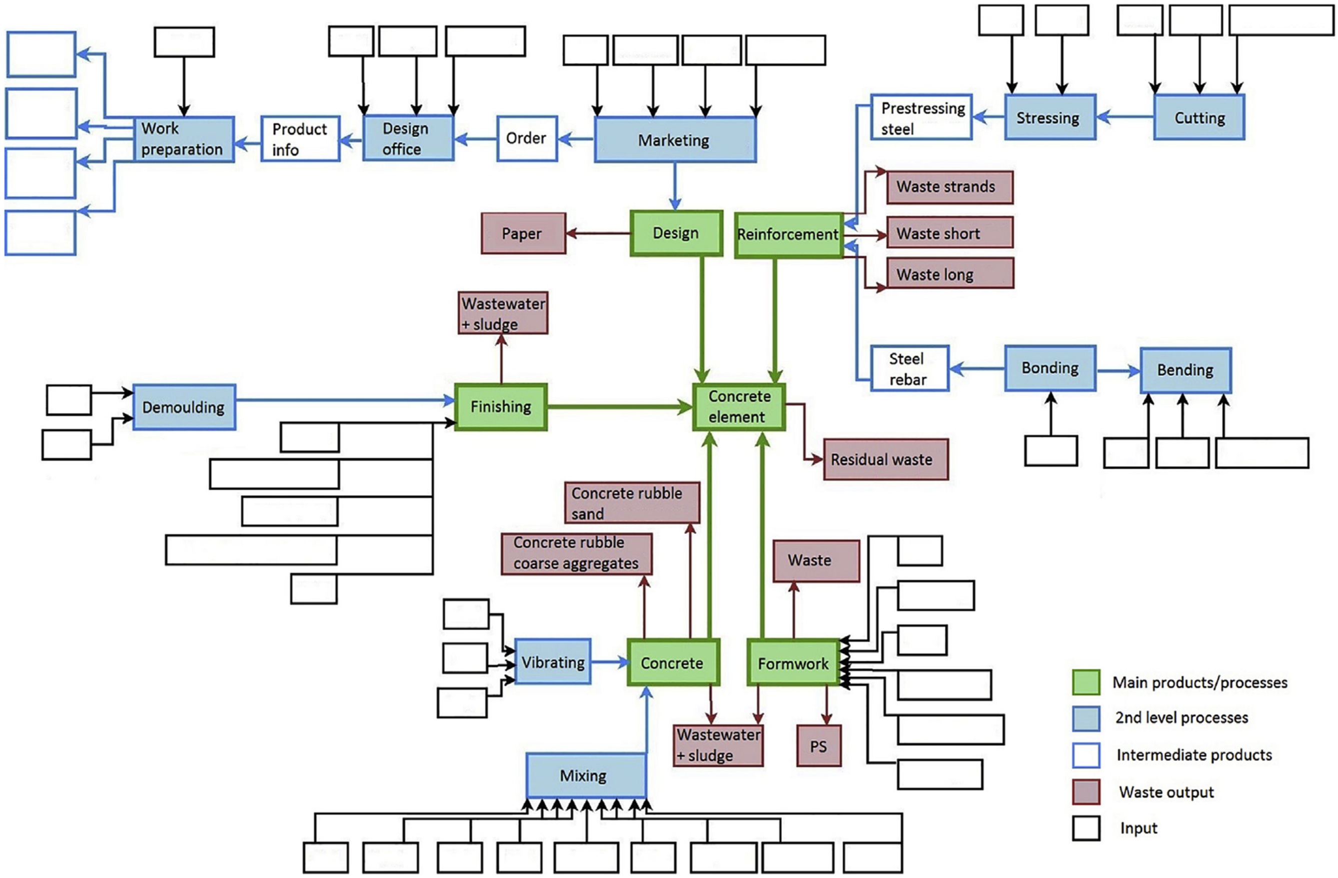

Fig. 1. Flow diagram of the analyzed concrete company.

Table 1
Processes used to build up the LCA.

Processes	Output quantity	Transport to concrete company	Waste
Raw materials	1 kg or 1 t	8–1800 tkm	–
Transport	1 tkm	–	–
Concrete mixtures	# kg/m^3 + # kg/m^3 waste	–	x
N 1	*2465 + 120.8*		
N 2	*2428 + 120.8*		
N 3	*2451 + 120.8*		
N 4	*2488 + 335.6*		
N 5	*2409 + 120.8*		
Reinforcement	1 kg + # kg waste	0.1 tkm	x
- Bars	*+ 0.303 kg waste*		
- Strands	*+ 0.096 kg waste*		
Cleaning water	1 kg + 0.057 kg waste	–	x
Working hours	1 h	–	–
Energy	1 kWh	–	–

– = not incorporated in the processes.
x = incorporated in the processes.

Table 2
Composition of the concrete mixtures [kg/m^3].

N	Cement	Filler	Water	Coarse aggregates			Fine aggregates		Additives	
				CA 1	CA 2	CA 3	Sand 1	Sand 2	Add 1	Add 2
1	349	30	140	0	0	1241	0	701	0	3.6
2	417	0	167	0	0	1155	0	683	0	5.3
3	355	0	149	0	1243	0	0	702	0	2.9
4	335	0	127	1194	0	0	832	0	0.8	0
5	452	0	181	0	0	853	917	0	0	5.9

CA 1, CA 2, CA 3 = three types of coarse aggregates (more specific details cannot be mentioned because of confidentiality).
Add 1, Add 2 = two types of additives (more specific details cannot be mentioned because of confidentiality).

Table 3
Assemblies used to build up the LCA (quantities according to the specified FU of one m^3 of finished concrete product with a service life of 50 years).

Assemblies	Output quantity	Difference beams, TT, floor	Current practice
Energy	18 kWh/m^3	Floor: +heat (+3.165 kWh/m^3)	Electricity (+heat)
Formwork	# kg/m^3	–[a]	0% recycled polystyrene + lubricating oil
Beam	PS: 0.039		
	Oil: 0.04		
TT	PS: 0.039		
	Oil: 0.16		
Floor	PS: 0.108		
	Oil: 0.11		
Concrete	# kg/m^3	# concrete mixtures[a]	Result of processes
Beam	2435		
TT	2409		
Floor	2488		
Reinforcement	# kg/m^3	Floor: only strands[a]	Result of processes
Beam	Bars: 66.9		
	Strands: 74.4		
TT	Bars: 43.5		
	Strands: 31.3		
Floor	Bars: –		
	Strands: 38.5		
Cleaning	85.71 kg/m^3	–	Result of processes
Maintenance	# kg/m^3	–[a]	Alkyd paint
Beam	3.75		
TT	14.35		
Floor	9.86		
Transport to building site	500 tkm[b]	–	Truck EURO 5
Waste	# kg/m^3	# mixtures and reinforcement[a]	Result of processes
Beam	Concrete: 120.8		
	Steel: 27.4		
TT	Concrete: 120.8		
	Steel: 13.7		
Floor	Concrete: 335.6		
	Steel: 3.7		
Finished product	#p/m^3	Use of different assemblies	Result of assemblies
Total production	#p/m^3	N/A	Result of assemblies
Beam	0.307		
TT	0.102		
Floor	0.590		

PS = Polystyrene.
Oil = Formwork oil.
p = summation (finished product) or percentage distribution (total production) per m^3 of all contributing assemblies.
N/A = Not applicable.
[a] These differences are a result of different proportions and dimensions/reinforcement quantity.
[b] The transport distance is assumed to be 200 km and the mass to be transported 2500 kg/m^3.

4.2. Ecological alternative

4.2.1. Background

Many of the previous studies in literature have examined how the composition of a concrete mixture can be made more sustainable. The options suggested in literature were assessed on feasibility for this study. Since cement is a large polluting factor, the most frequent option is to substitute a part of the cement content in the concrete mixture by a supplementary cementitious material (SCM). Several options have been investigated such as partial replacement by fly ash [23–26], limestone [27], blast-furnace slag [28,29], fine bagasse ash [30], … Next to this, using recycled aggregates instead of natural aggregates might be a beneficial option. For this purpose, research has been done about the use of glass aggregates in concrete, which leads to the so-called ‘glascrete’ [31,32]. In addition, waste of the marble industry [33], the use of construction and demolition waste (C&D waste) [34] or basalt aggregates [35] can be considered for substitution of aggregates. Even the use of wood [36] and shredded tires [37] has been studied. Furthermore, there are a lots of reports available regarding the recycling of water in concrete production [38–40].

Next to these options to make the concrete mixture itself more sustainable, other options to reduce the environmental impact over the total life cycle of a concrete product can be found in literature. Reusing or recycling reinforcement steel [41,42], optimization of the use of energy in the company [43,44], using another transport medium or lowering the transport distances and changing waste into recyclable materials [42] are among the numerous possibilities.

A lot of options to obtain a more ecological production in the specific concrete company have been considered. The choice whether the different options could be applied, was made based on the fact that every adjustment had to be achievable in the company. For example, the compressive strength class of the concrete had to be maintained.

4.2.2. Processes

The concrete compositions were adjusted by the substitution of a part of the cement content by fly ash. Here, it is important to take into account the k-value concept of the standard NBN EN 206:2014 [45], which limits the amount of replacement by fly ash. The newly composed binder (cement + fly ash) was incorporated in the LCA by a new process with an output of 1 tonne binder fabricated with 750 kg Portland cement and 250 kg fly ash. The process of Portland cement was available in the Ecoinvent database and could be used directly. In return, a new process for fly ash was developed in SimaPro, based on information about different inputs and outputs for the production and treatment of fly ash, listed in Chen et al. [46].

The ecological variant of the reinforcement steel consists of reinforcement steel made out of 80% recycled material. This applies to both the steel bars and prestressing steel strands. The non-ecological variant of both reinforcement processes is assumed to consist of 100% virgin material. In this way, these last processes consist of 100% standard reinforcement steel, of which no recycling percentage was documented in the database.

For the electricity process, the ecological version exists of a combination of electricity obtained from hydropower, nuclear energy, photovoltaic installations and wind power. The ecological alternatives for the processes are summarized in Table 4.

4.2.3. Assemblies

In contrast to the traditional formwork with non-recycled polystyrene, the ecological version of the formwork uses 100% recycled polystyrene. The process of the maintenance uses a solvent-based, or alkyd paint in the traditional alternative. This is changed by acrylic varnish (water-based) in the ecological option. The ecological versions of the remaining assemblies result from the already discussed processes, as is listed in Table 5.

4.2.4. Waste scenarios

Two waste scenarios are composed in the LCA: a scenario with almost no recycling and a scenario with as much recycling options as possible. The treatment of waste is limited to the waste produced during the concrete production phase. The chosen waste treatments in each waste scenario are listed in Table 6 and Table 7. The respective waste treatments were adjusted to fit the specificities of the co-operating manufacturer and the cradle to gate system with options. Therefore some remarks have to be made:

1. In contrast to the current practice in which the wastewater is drained to the sewage, the cleaning water will be purified and will be re-used for the production of concrete in the ecological version of the model. In correspondence with these ecological conditions, a wastewater treatment which incorporates a purification phase is chosen out of the databases, to obtain an estimation of the possible impact of such an additional treatment.
2. In the traditional version of the model the production waste of concrete is thought to be broken and reused for road construction. The resulting positive impact is not accounted for because this is not incorporated in the system boundaries. In the ecological version, the concrete waste is reused in less demanding concrete applications. This results in the waste treatment into two recycled products: sand and coarse aggregates. In relation to 1 kg of waste, an amount of 0.1 kg and 0.5 kg respectively, are supposed to be obtained by recycling. These amounts were added as output to the techno sphere in the waste treatment “Disposal, building, concrete, not reinforced, to recycling/CH S eco”.

Table 4
Ecological process alternatives.

Processes	Ecological variant
Raw materials	Cement + FA[a]
Transport	–
Concrete mixtures	–
Reinforcement	80% recycled
Cleaning water	–
Working hours	–
Energy	x[b]

[a] FA = fly ash.
[b] Ecological alternative for electricity: combination of electricity obtained from hydropower, nuclear energy, photovoltaic energy and wind power.

3. The steel waste is considered as a recyclable product. For this reason, 95% of the reinforcement steel is added to the ‘outputs to the techno-sphere’ in the waste treatment of reinforcement steel, and can in this way be recycled and reused. The remaining 5% is supposed to go to a landfill.

4.2.5. Lifecycles

The different traditional and ecological finished product assemblies were each time combined with the general and recycling waste scenarios respectively, to compose the life cycles of the beams, TT-elements and floor slabs. Additionally the same is done with the total production assemblies to compose the total life cycle of the cradle to gate system with options.

4.3. Comparison of main structure types

In addition to the previous mentioned assemblies, for each type of structure there has been made a specific ‘calculation assembly’ to be able to compare the different structures, based on their load bearing capacity. As is mentioned in Habert et al. [47], it can be useful to make for example a product with less volume, and hence a lower cement content, but with a higher strength, so it can bear the same load.

For each structure a medium sized element was chosen out of the product range of the company. The payload, span and geometry of these elements were combined into a parameter expressed in kN/m^3. The applied values are listed in Table 8. By dividing the functional unit of 1 m^3 by this parameter, it is possible to estimate the ecological impact of a structure in terms of the m^3 of concrete needed per kN load. This quantity is shown in the last column of Table 8.

5. Life cycle impact assessment and interpretation

As is mentioned in the scope definition, the life cycle impact assessment is based on both a problem oriented method (EPD 2008) and a damage oriented method (Eco-indicator 99) to get better idea of the impact.

5.1. Assessment of the traditional production method

Regarding the traditional production, in Fig. 2 the relative contribution of the different processes according to the Eco-indicator 99 method is presented. Reinforcement steel (29%), Portland cement (27%) and transport by lorry (20%) clearly have most impact on the environment. In addition, maintenance, aggregates, final disposal of concrete and fabrication may certainly not be neglected as well. The fabrication component incorporates electricity, process water, heat, polystyrene, lubricating oil and tap water.

In Fig. 3 the impact is shown for the processes with the largest effect according to both the traditional and the ecological production method. For the global warming (GWP), ozone layer depletion (ODP) and photochemical oxidation (PO), a cut-off factor of 1% is chosen, and for the acidification potential (AP), eutrophication (EP), non-renewable fossil energy (NrF) and Eco-indicator 99 (Eco-ind 99) a cut-off factor of 2% is chosen. The cut-off factors determine that the processes which contribute less than 1% and 2% respectively to the total impact, are omitted in the equations. In this way, the different impact categories and cut-off factors allow to represent the contributing processes adequately in the graphs.

Considering the various assessment methods in Fig. 3, the processes of steel, Portland cement, transportation by lorry,

Table 5
Ecological assembly alternatives.

Assemblies	Traditional alternative	Ecological alternative
Energy	Electricity (+heat)	Result of processes
Formwork	0% recycled polystyrene + lubricating oil	100% recycled polystyrene + lubricating oil
Concrete	Result of Table 1	Result of Table 1
Reinforcement	Result of Table 1	Result of Table 1
Cleaning	Result of Table 1	–
Maintenance	Alkyd paint	Acrylic varnish
Transport to building site	Truck EURO 5	–
Waste	Result of Table 1	Result of Table 1
Finished product	Result of Table 3	Result of Table 3
Total production	Result of Table 3	Result of Table 3

– = no ecological alternative is provided.

Table 6
Waste scenario traditional.

Waste type	Waste treatment
Concrete wastes	Disposal, building, concrete, not reinforced, to final disposal/CH S
Concrete sludge	Disposal, building, concrete, not reinforced, to final disposal/CH S
Reinforcement wastes	Disposal, building, reinforcement steel, to recycling/CH U
Cleaning water	Treatment, sewage, to wastewater treatment, class 3/CH S

Table 7
Waste scenario recycling.

Waste type	Waste treatment
Concrete wastes	Disposal, building, concrete, not reinforced, to recycling/CH S
Concrete sludge	Disposal, building, concrete, not reinforced, to recycling/CH S
Reinforcement wastes	Disposal, building, reinforcement steel, to recycling/CH U
Cleaning water	Treatment, concrete production effluent, to wastewater treatment, class3/CH S

Table 8
Values for comparison main structure types.

Structure	Payload [kN/m]	Surface dimensions [m]	Volume [m^3]	Total load [kN]	Load/m^3 [kN/m^3]	Qty. used in assembly [m^3/kN]
Beam	21	20	4.65	420	90.3	0.0111
TT	14	11 × 2.4	3.96	370	93.3	0.0107
Floor	8	11 × 1.2	2.06	106	51.3	0.0195

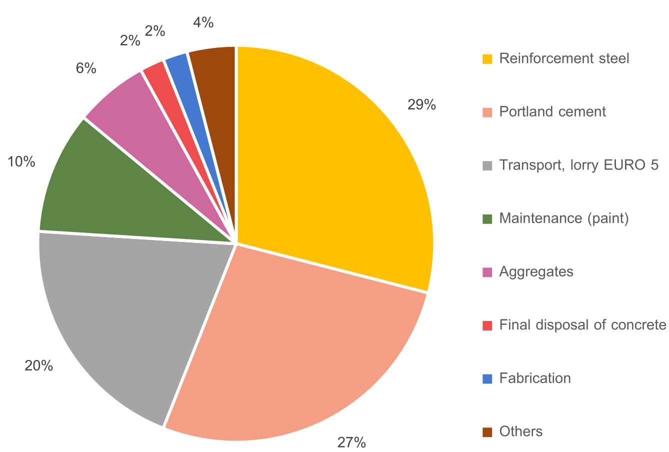

Fig. 2. Relative contribution to the overall ecological impact (according to Eco-indicator 99) of the different processes according to the current practice.

maintenance of concrete (paint) and final disposal of concrete affect the environment the most. This is true for all impact categories shown.

5.2. Comparison of traditional and ecological production

To obtain a more ecological production in the concrete company, it becomes clear from Fig. 3 that by using reinforcement steel with a recycled component of 80%, lowering the amount of Portland cement and altering the type of paint for maintenance, a significant improvement can be achieved. Changing the transport by lorry to transport by ship would also result in a reduction in impact on the environment. Additionally, changing the final disposal of concrete aggregates into a recycling phase is also of positive influence. All these adaptions could result in a reduction of the impact on the environment of 20–30%, depending on the assessment method used.

Because of the chosen cut-off factors, the presentation of the contribution of the aggregates in Fig. 3 is limited to coarse aggregates 1 and 2, which are mentioned in Table 2. When counting all coarse and fine aggregates together, the total of aggregates has an impact of 6% on the total non-eco production in the company according to the Eco-indicator 99 method, which is also shown in Fig. 2. In the same way, electricity, process water, heat, polystyrene, lubricating oil and tap water can be combined to an overall impact of the fabrication component of 2% on the total system. The processes in this percentage distribution interchange when looking at the environmental variant in Fig. 4. Transport by lorry together

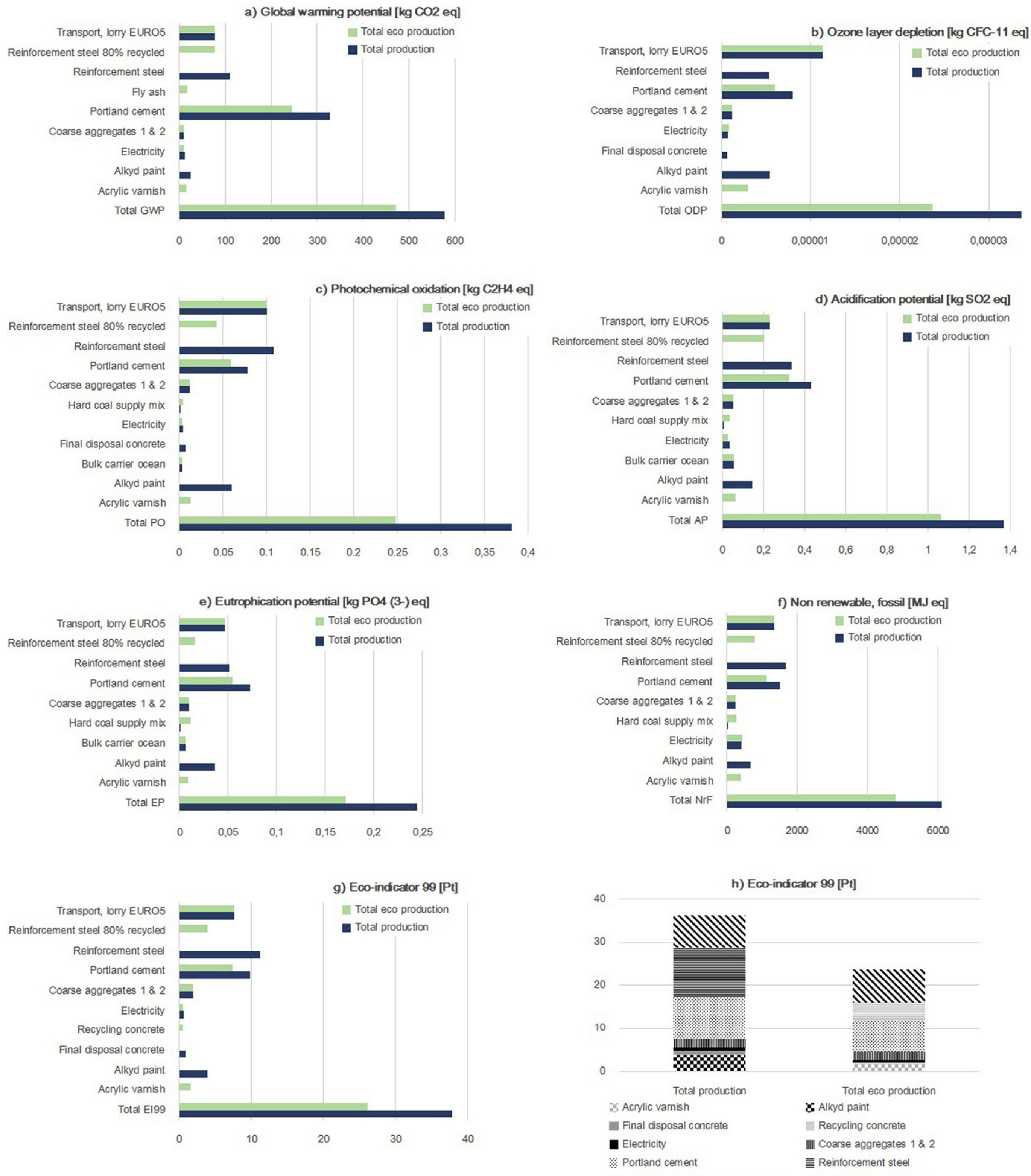

Fig. 3. Impact assessment with FU = '1 average m^3 of the total production': a) Global warming potential (GWP), b) Ozone layer depletion (ODP), c) Photochemical oxidation (PO), d) Acidification potential (AP), e) Eutrophication potential (EP), f) Non renewable fossil (NrF) and g) + h) Eco-indicator 99 (Eco-ind 99) (cut-off factor for GWP, ODP, PO = 1%, for AP, EP, NrF, Eco-ind 99 = 2%).

with Portland cement (and fly ash) have gained in importance since the use of recycled metals for reinforcing steel significantly lowers in impact on the environment.

5.3. Comparison of beams, TT-elements and floors

In Fig. 5 the Eco-indicator 99 method is used to compare the

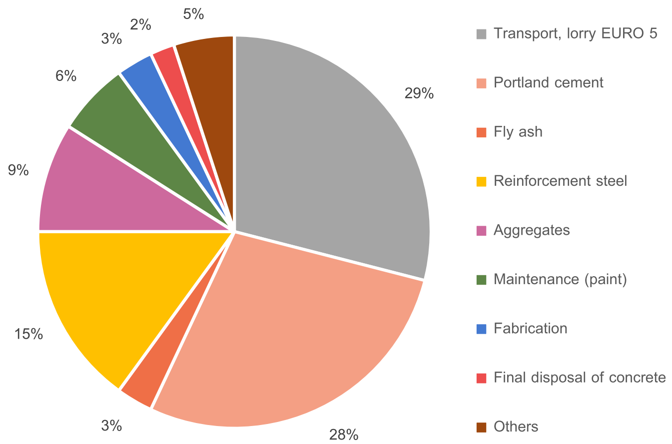

Fig. 4. Relative contribution to the overall ecological impact (according to Eco-indicator 99) of the different processes according to the ecological variant.

higher impacts than floor slabs. The reason for this can be found in the earlier mentioned fact that beams contain on average twice as much reinforcement than TT-elements and four times as much in comparison with floor slabs. This is also the explanation for the higher absolute values of the impact of waste treatment of beams relative to the impacts of TT-elements and floor slabs.

Floors have a higher impact on the environment in terms of formwork (followed by TT-elements) and they also need an extra amount of energy for heating during fabrication. Next to this, looking at the aspect of maintenance, TT-elements have the largest impact followed by floor slabs. In this respect, one might presume that beams would have the lowest environmental footprint, compared to TT-elements and floors. However, the opposite seems true, because of the higher amount of reinforcement steel per cubic meter in beams. This highlights the fact that the amount of reinforcement steel in each structure type is of great significance in this study.

Table 9 presents the total average values of one cubic meter of a

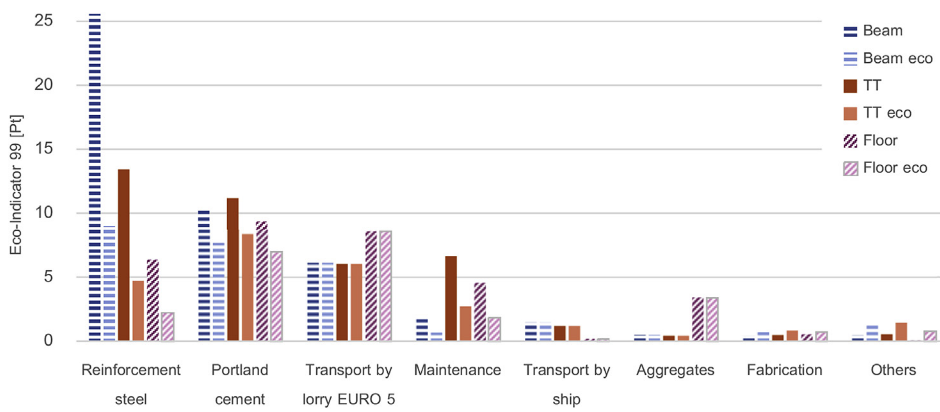

Fig. 5. Impact per process and per main structure type (Eco-Indicator 99 [Pt]).

standard and eco version of the beams, TT-elements and floor slabs based on their material content. Also in this case, reinforcement steel, Portland cement, transport by road, maintenance and aggregates occur as very important processes. Beams contain on average twice as much reinforcement as TT-elements and four times as much as floor slabs. This is clearly reflected in the results of the reinforcement impact.

The impacts of the categories of transport by lorry and aggregates result in higher values for floor elements in comparison to the impacts for beams and TT-elements. The reason for this can mainly be found in the fact that in floor elements the use of a certain kind of coarse aggregates is a lot higher. For this material a longer road transport is needed and the processing of it causes a larger impact on the environment than the other used aggregates.

The results of the maintenance process reflect the sizes of the surfaces of the different structures that need to be covered with paint. In the 'others' category, it is remarkable that there is an amount of impact left that is caused by the ecological variants of the structures. The main reason for this result can be found in the fact that in each ecological variant the production chain of fly ash causes an additional impact on the environment.

When comparing beams, TT-elements and floors in Fig. 6, it becomes clear that the waste treatments often create a negative impact in the different categories, mostly because of the recycling of steel. In this way the total impact of the different end products decreases. The impact of beams is most of the times higher than the impact caused by TT-elements, and these have in turn mostly beam, TT-element and floor. In this way it is possible to calculate an approximate average value of a specific beam, TT-element or floor used in buildings/structures composed of these types of prefabricated elements, by multiplying its volume with these values.

When considering the overall production of structures in the considered concrete company during an average year, another sequence of the results can be noticed compared to Fig. 6. Since floors are produced a lot more in this company, and beams second most, especially floors contribute to the environmental impact of the concrete company, followed by beams.

Using the calculation assemblies mentioned in Section 4.3 and their respective life cycles, it is possible to compare the three main structure types (beams, TT-elements and floor slabs) according to their load bearing capacity. In Fig. 7 it is clearly seen that floor elements are the least suitable, regarding their high impact on the environment. TT-elements however can be seen as the best choice. The reason for these results is found in the fact that there is generally more need for material in floor elements to obtain the same load bearing capacity than in beams or TT-elements.

6. Conclusions

Throughout this study, life cycle assessment was used to evaluate the environmental impact of the different processes in the production of a high strength concrete element manufacturer. The rather unique close collaboration with industry allowed for environmental impact calculations that are based on very reliable

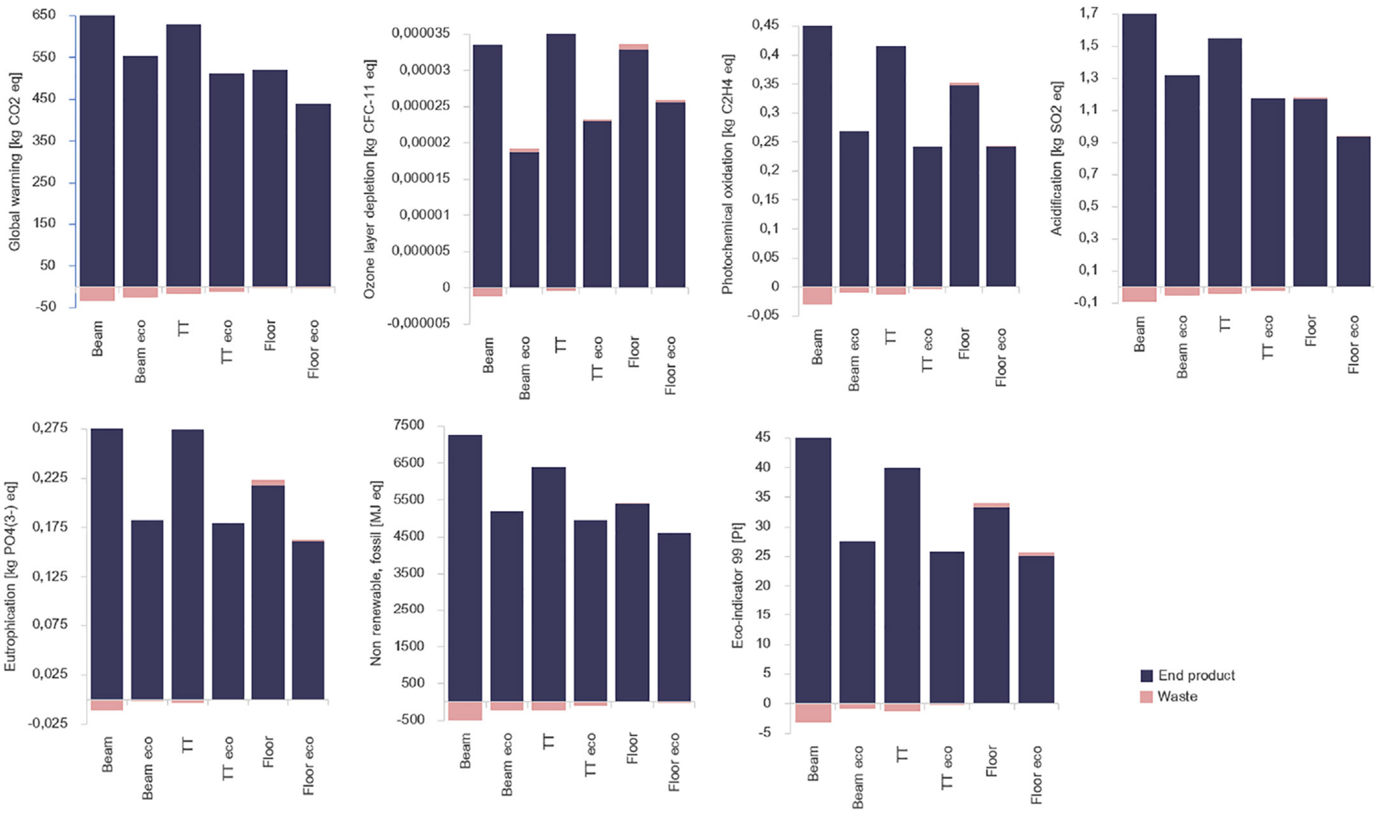

Fig. 6. Impact assessment of beams, TT-elements and floor slabs with the EPD 2008 method and Eco-indicator 99 method.

Table 9
Impact assessment of beams, TT-elements and floor slabs with the EPD 2008 method and Eco-indicator 99 method.

	Beam	Beam eco	TT	TT eco	Floor	Floor eco
Global warming [kg CO2 eq]	655	529	612	500	521	436
Ozone layer depletion [kg CFC-11 eq]	3.2E-05	1.9E-05	3.5E-05	2.3E-05	3.4E-05	2.6E-05
Photochemical oxidation [kg C2H4 eq]	0.42	0.26	0.40	0.24	0.35	0.24
Acidification [kg SO2 eq]	1.63	1.27	1.51	1.15	1.18	0.94
Eutrophication [kg PO4(3-) eq]	0.27	0.18	0.27	0.18	0.22	0.16
Non renewable, fossil [MJ eq]	6748	4966	6156	4840	5420	4604
Eco-indicator 99 [Pt]	43.54	26.83	38.66	25.56	34.08	25.70

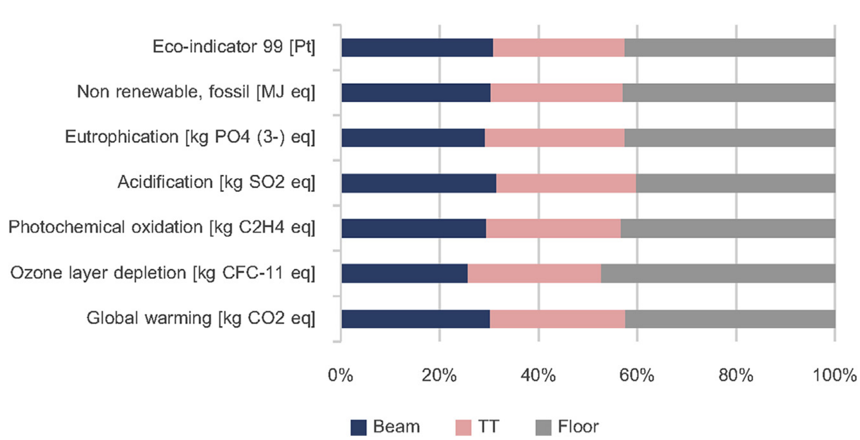

Fig. 7. Evaluation of the different types of structure based on their load bearing capacity.

information regarding the operation of an actual precast concrete plant directly provided by the manufacturer. Based on production site specific data obtained as such, the life cycle inventory was built and LCA calculations were performed accordingly. This most certainly contributed to the accuracy of the reported environmental scores. Moreover, the study provides a set of comprehensive environmental profiles for three types of commonly used precast concrete elements (beams, TT-elements and floors) which can serve as direct input for LCA studies that focus on whole buildings/ structures.

The main conclusions of the impact assessment show that the reinforcing and prestressing steel (29%) and the cement (27%) dominate the impact contributions, but other factors such as transport by road (20%), maintenance (10%), aggregates (6%), fabrication (2%), and concrete waste production during fabrication (2%) are also non-negligible. A further impact study shows that the use of cement replacing materials, the use of recycled reinforcement steel, recycling aggregates from the production waste and several smaller adaptions can potentially reduce the impact on the environment with 20–30%, depending on the assessment method used.

References

[1] S.E. Chidiac, Sustainability of civil engineering structures - durability of concrete, Cem. Concr. Compos. 31 (2009) 513–514.
[2] D. Chisholm, TR 14 Best Practice Guide for the Use of Recycled Aggregates in New Concrete, Cement & Concrete Association of New Zealand, 2011.
[3] The Cement Sustainability Initiative, Recycling Concrete, World Business Council for Sustainable Development, Switzerland, 2009.
[4] Cembureau (the European Cement Association), Key Facts & Figures [Online]. Available, Cembureau, 2015 [Accessed 16 10 2015], http://www.cembureau.be/about-cement/key-facts-figures.
[5] R. Swamy, Holistic design – key to sustainability in concrete construction, Indian Concr. J. (2003) 1291–1299. Sept.
[6] D. Flower, J. Sanjayan, Green house gas emissions due to concrete manufacture, Int. J. LCA 12 (5) (2007) 282–288.
[7] I. Holton, J. Glass, A.D. Price, Managing for sustainability: findings from four company case studies in the UK precast concrete industry, J. Clean. Prod. 18 (2010) 152–160.
[8] European Committee for standardisation, ISO 14040:2006. Environmental Management - Life Cycle Assessment - Principles and Framework, Belgisch Instituut voor Normalisatie (BIN), Brussel, 2006.
[9] O. Ortiz, F. Castells, G. Sonnemann, Sustainability in the construction industry: a review of recent developments based on LCA, Constr. Build. Mater. 23 (2009) 28–39.
[10] A. Rashid, S. Yusoff, A review of life cycle assessment method for building industry, Renew. Sustain. Energy Rev. 45 (2015) 244–248.
[11] M. Dijk, I. Blom, T. Salet, P. Marinus, Environmental impact as a parameter in concrete structure parametric associative models, Constr. Build. Mater. 67 (2014) 360–365.
[12] J.G. Vogtländer, A. Bijma, H.C. Brezet, Communicating the eco-efficiency of products and services by means of the eco-cost/value model, J. Clean. Prod. 10 (2002) 57–67.
[13] J.G. Vogtländer, H.C. Brezet, C.F. Hendriks, "The virtual eco-costs '99, Int. J. LCA 6 (3) (2001) 157–166.
[14] T. Hong, C. Ji, M. Jang, H. Park, Assessment model for energy consumption and greenhouse gas emissions during building construction, J. Manag. Eng. (March/April 2014) 226–235.
[15] M. Buyle, J. Braet, A. Audenaert, Life cycle assessment in the construction sector: a review, Renew. Sustain. energy Rev. 26 (2013) 379–388.
[16] European committee for standardisation, ISO 14044:2006. Environmental Management - Life Cycle Assessment - Requirements and Framework, Belgisch Instituut voor Normalisatie (BIN), Brussel, 2006.
[17] Scientific Applications International Corporation (SAIC), Life Cycle Assessment: Principles and Practice, U.S. Environmental Protection Agency, Cincinnati, Ohio, 2006.
[18] R. Frischknecht, N. Jungbluth, Overview and Methodology. Final Report Ecoinvent v2.0 No.1, Swiss Center for Life Cycle Inventories, St-Gallen, Switzerland, 2007.
[19] P. Van den Heede, N. De Belie, Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: literature review and theoretical calculations, Cem. Concr. Compos. 34 (2012) 431–442.
[20] The International EPD Cooperation (IEC), EPD General Programme Instructions - for Environmental Product Declarations, EPD Version 1.0, The International EPD Cooperation (IEC), 2008.
[21] Harry Baayen, Eco-indicator 99: Manual for Designers - a Damage Oriented Method for Life Cycle Impact Assessment, Ministry of Housing, Spatial Planning and the Environment, The Hague, The Netherlands, 2000.
[22] A.P. Gursel, E. Masanet, A. Horvath, A. Stadel, Life-cycle inventory analysis of concrete production: a critical review, Cem. Concr. Compos. 51 (2014) 38–48.
[23] Headwaters Resources, Fly Ash for Concrete - Fly Ash: the Modern Pozzolan Improving Concrete Performance Enhancing Our Environment, Utah: Headwaters Resources.
[24] R. Liu, S.A. Durham, K.L. Rens, A. Ramaswami, Optimization of cementitious material content for sustainable concrete mixtures, J. Mater. Civ. Eng. (June 2012) 745–753.
[25] K.H. Obla, Specifying Fly Ash for Use in Concrete, Concrete InFocus, 2008, pp. 60–66.
[26] S.L. Valcke, R.B. Polder, T.G. Nijland, G.A. Leegwater, J.H. Visser, A.J. Bigaj-van Vliet, "High filler concrete using fly ash - chloride penetration and microstructure, Heron 57 (3) (2012) 169–184.
[27] K. Celik, C. Meral, A.P. Gursel, P.K. Mehta, A. Horvath, P.J. Monteiro, Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended portland cements containing fly ash and limestone powder, Cem. Concr. Compos. 56 (2015) 59–72.
[28] A. Lübeck, A. Gastaldini, D. Barin, H. Siqueira, Compressive strength and electrical properties of concrete with white Portland cement and blast-furnace slag, Cem. Concr. Compos. 34 (2012) 392–399.
[29] K.Y. Yeau, E.K. Kim, An experimental study on corrosion resistance of concrete with ground granulate blast-furnace slag, Cem. Concr. Res. 35 (2005) 1391–1399.
[30] P. Muangtong, S. Sujjavanich, S. Boonsalee, S. Poomiapiradee, D. Chaysuwan, "Effects of fine bagasse ash on the workability and compressive strength of mortars, Chiang Mai J. Sci. 40 (1) (2013) 126–134.
[31] W. Jin, C. Meyer, S. Baxter, Glascrete" - concrete with glass aggregate, ACI Mater. J. (March-April 2000) 208–213.
[32] R.-U.-D. Nassar, P. Soroushian, Strength and durability of recycled aggregate concrete containing milled glass as a partial replacement for cement, Constr. Build. Mater. 29 (2012) 368–377.
[33] P. Martins, J. de Brito, A. Rosa, D. Pedro, Mechanical performance of concrete with incorporation of coarse waste of the marble industry, Mater. Res. 17 (5) (2014) 1093–1101.
[34] M. Behera, S. Bhattacharyya, A. Minocha, R. Deoliya, S. Maiti, Recycled aggregate from C&D waste & its use in concrete - a breakthrough towards sustainability in construction sector: a review, Constr. Build. Mater. 68 (2014) 501–516.
[35] C. Ingrao, A. Lo Giudice, C. Tricase, C. Mbohwa, R. Rana, The use of basalt aggregates in the production of concrete for the prefabrication industry: environmental impact assessment, interpretation and improvement, J. Clean. Prod. 75 (2014) 195–204.
[36] C. Becchio, S.P. Corgnati, A. Kindinis, S. Pagliolico, Improving environmental sustainability of concrete products: investigation on MWC thermal and mechanical properties, Energy Build. 41 (2009) 1127–1134.
[37] A.A. Yasin, Using shredded tires as an aggregate in concrete, Contemp. Eng. Sci. 5 (10) (2012) 473–480.
[38] Z. Ismail, E. Al-Hashmi, Assessing the recycling potential of industrial wastewater to replace fresh water in concrete mixes: application of polyvinyl acetate resin wastewater, J. Clean. Prod. 19 (2011) 197–203.
[39] J. Férriz-Papi, "Recycling of fresh concrete exceeding and wash water in concrete mixing plants, Mater. Constr. 64 (313) (2014).
[40] S. Ekolu, A. Dawneerangen, "Evaluation of recycled water recovered from a ready-mix concrete plant for reuse in concrete, J. South Afr. Inst. Civ. Eng. 52 (2) (2010) 77–82.
[41] C. Broadbent, Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy, Int. J. Life Cycle Assess. (2016), http://dx.doi.org/10.1007/s11367-016-1081-1.
[42] V.W. Tam, Rate of reusable and recyclable waste in construction, Open Waste Manag. J. 4 (2011) 28–32.
[43] V. Introna, V. Cesarotti, M. Benedetti, S. Biagiotti, R. Rotunno, Energy management maturity model: an organizational tool to foster the continuous reduction of energy consumption in companies, J. Clean. Prod. 83 (2014) 108–117.
[44] B. Milfelner, D. Mumel, A.P. Korda, Management perceptions of renewable energy use and efficient energy consumption: a case of slovenian companies, Environ. Eng. Manag. J. 13 (3) (2012) 643–652.
[45] European Committee for Standardisation, Concrete - Specification, Performance, Production and Conformity, Belgisch Instituut voor Normalisatie (BIN), Brussel, 2014.
[46] C. Chen, G. Habert, Y. Bouzidi, A. Jullien, A. Ventura, LCA allocation procedure used as an incitative method for waste recycling: an application to mineral additions in concrete, Resour. Conserv. Recycl. 54 (2010) 1231–1240.
[47] G. Habert, D. Arribe, T. Dehove, L. Espinasse, R. Le Roy, Reducing environmental impact by increasing the strength of concrete: quantification of the improvement to concrete bridges, J. Clean. Prod. 35 (2012) 250–262.