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Decision-making Tool for the Assessment and Selection of Construction Processes Based on Environmental Criteria: Application to Precast and Cast-in-situ Alternatives

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Abstract

This paper presents a quantitative environmental impact assessment tool for the decision making of construction processes including structures, infrastructures and buildings by means of an Environmental Impact Index (EII) to be applied at design and/or construction stages. The research is based on multi-attribute utility theory, interviews with experts representatives of the different stakeholders in construction, and an analysis of fifty-nine European and Spanish environmental legislative acts. The resulting tool was applied to two construction alternatives for road drains (one precast and one cast-in-place). The findings show that the tool enables the prioritisation of construction processes and the selection of the best alternative in terms of environmental impact and that the results are stable to reasonable weight variations. The tool contributes to decision making in the context of project management in construction: it can help professionals in public administration, and design and construction companies. It helps to quantify the cradle-to-gate impact of construction work, which has usually been less studied than the operational impact in the life-cycle assessment of buildings. The tool is being piloted in construction projects of the Barcelona City Council.

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1. Introduction

The construction industry is one of the largest consumers of energy, material resources and water, and it is responsible for a significant portion of pollution through its harmful emissions and waste (Bakhoum and Brown, 2012; Huang et al., 2013; and Li et al., 2016). According to Eurostat, the domestic material consumption in the EU accounted for 6.6 million tonnes in 2013 from which 46% were non-metallic minerals including sand and gravel, which are mainly used by the construction industry. In 2012, the total waste and total hazardous waste generated in the EU amounted to 2514 and 100 million tonnes respectively, with a construction contribution of 821 (33%) and 16 (16%) million tonnes respectively.

Making construction more environmentally friendly improves efficiency and profits. These improvements result from the efficient use of resources, energy savings, increased recycling, reduced waste disposal costs and lower transport costs because of local suppliers (ICE et al., 2002). The selection of the construction process has key implications on the environmental performance (Toller et al., 2013). The environmental impact of construction work should thus be considered in the design of the construction process and during the construction work itself.

There is a lack of information regarding sustainability related to construction (Bakhoum and Brown, 2012). Modest literature focus towards energy reduction within the construction process (Davies et al., 2013). It is difficult to arrive at greenhouse gas (GHG) emission estimates that can be reliably used to discriminate between alternatives due to the uncertain and non-prototypical nature of construction processes (Cass and Mukherjee, 2011). Quantifying civil engineering projects in terms of sustainability is a new challenge for the civil engineering industry (Spencer et al., 2012).

The environmental assessment of buildings seems to be more developed than that of the infrastructures. Nevertheless, Ng et al. (2013) found that around a half of the indicators of six widely recognised building environmental assessment tools (BREEAM, BEAM Plus, LEED, CASBEE, Green Mark, and Green Star) are qualitative, not quantitative, and that they lack a quantitative method to analyse life-cycle CO_2 emissions.

Cradle-to-gate impacts in buildings (those from material extraction, manufacturing, transport to site, and onsite construction) are often ignored because they have historically been outweighed by operational impacts (Davies et al., 2013; Dimoudi and Tompa, 2008; Hong et al., 2014; Ng et al., 2013; Ortiz et al., 2010; and Russell-Smith and Lepech, 2014). According to a review performed by Faludi and Lepech (2012), occupational impacts account for 90-95% of life-cycle energy consumption, 80% of life-cycle CO_2 emissions and 65% of life-cycle SO_2 and NO_x emissions. However, cradle-to-gate impacts become a larger percentage of a building's total life cycle impacts as the use phase impacts decrease due to more efficient systems (Motuzienė et al., 2016). In a study performed by Faludi and Lepech (2012), the cradle-to-gate impact of a prefabricated commercial building with 30% of power supplied by photovoltaics is a third of the total life-cycle environmental impact.

The main objective of this research is to provide a tool that helps to choose the best construction process in terms of environmental impact for a given project once the main characteristics of the project have been defined. A second objective is to provide a tool to compare the real environmental impact produced by a construction work with the impact predicted from the project.

The research presented in this paper addresses these challenges and defines a new systematic quantitative tool with the following key strengths: (1) it is a useful tool for comparing construction alternatives, (2) it quantifies the cradle-to-gate impact of construction work, which has usually been less studied than operational impact in the life-cycle assessment of buildings, (3) it can be applied to different types of construction work including structures, infrastructures and buildings, and (4) it can be applied at both pre-construction stage planning and at construction stage for monitoring.

2. Methods

Multi-criteria decision analysis is a valuable tool to assist the decision maker with the decision-making process and can be used to evaluate the environmental impact of construction work. The five main multi-criteria decision theories (ordinal multi-criteria methods, multi-objective mathematical programming, multi-attribute utility theory, outranking relation theory and preference disaggregation analysis) and their methods have been analysed for the research. The widely known multi-attribute utility theory (Keeney and Raiffa, 1976) has been selected for decision-making of construction processes as it helps solve discrete problems, it can be understood intuitively and it is based on a solid foundation (Casanovas-Rubio, 2014). It has been successfully applied to decision making in construction (Arif et al., 2016; and Perera et al., 2016) and to evaluate sustainability in construction, including the environmental impact (de la Fuente et al., 2016; and Wei et al., 2016). Based on the multi-attribute utility theory, new criteria, subcriteria, weights and indicators have been defined for developing the tool presented in this paper. Fig. 1 shows the steps followed to develop the tool. These steps are those of the multi-attribute utility theory adapted to the environmental impact of construction work.

2.1. Establishing the limits

The tool is defined to compare different construction processes (alternatives) for the same or very similar finished construction and same performance, thus, with the same environmental impact during the use phase. Consequently, the use phase does not help to discriminate between alternatives and, therefore, is not included in the study. The comparison focuses on the cradle-to-gate stages (the construction work itself and the previous stages) because they help to discriminate between construction processes (Fig. 2). Hence, the tool considers the embodied environmental impacts of construction materials.

2.2. Identification of environmental impacts

The identification of the environmental impacts caused by construction work was based on a first round of interviews with experts in decision making in construction, an analysis of fifty-nine European and Spanish legislative acts on environmental matters and the publications cited further on. The number of panel members for the first round of interviews was eleven representing the different stakeholders in construction: local, regional and state public administration, construction companies, environmental and engineering consultancy, concessionaires, academia and civil engineer associations. A larger number of European and Spanish environmental legislative acts were initially consulted. Those found to be more relevant to the research were analysed and are listed in Table 1.

The environmental impacts identified in this step are presented in Fig. 3. They are classified into three criteria and twelve subcriteria. The three criteria correspond to the main three aspects of construction work that cause an impact: input, output and interaction with the environment.

2.3. Environmental Impact Index (EII)

The Environmental Impact Index (EII_i) of the i construction process (alternative) is a measure of the environmental impact generated by the construction work and can be calculated according to equation (1). The best alternative is the one with the lowest EII.

$$EII_i = \sum_j w_j \cdot Env.Impact_{ij} \quad (1)$$

Where w_j is the global importance or weight assigned to the j subcriterion from Fig. 3. A set of reference weights for each type of environment is provided in section 2.4. The $Env.Impact_{ij}$ is the relative environmental impact produced by the i construction process for the j subcriterion. The $Env.Impact_{ij}$ can be defined using an alternative as reference as presented in equation (2).

$$Env.Impact_{ij} = \frac{I_{ij}}{I_{ref\,j}} \quad (2)$$

Where I_{ij} is the measurement of the j indicator of the i alternative and $I_{ref\,j}$ is the measurement of the j indicator for the alternative taken as reference. The impact of the alternatives is compared with the impact of a real alternative. The alternative taken as reference generates a relative impact equal to 1 and the remaining alternatives, a proportionate impact, higher or lower than 1. Equation (2) can be applied when there is at least an alternative that produces all the impact types generated by the other alternatives and that alternative would be the one taken as reference. Otherwise, if a measurement of the reference alternative were 0, according to equation (2), the relative impact of the rest of the alternatives would be infinite. In that case, the $Env.Impact_{ij}$ can be defined as presented in equation (3), using the alternative with the greatest impact for each subcriterion as reference.

$$Env.Impact_{ij} = \frac{I_{ij}}{max\,\{I_{ij}\}_{j=ct.}} \tag{3}$$

Where $max\,\{I_{ij}\}_{j=ct.}$ is the maximum measurement of the *j* indicator among all the alternatives considered. The relative impact can, thus, adopt values between 0 and 1. All the relative impacts of all the alternatives must be calculated using the same equation, either (2) or (3), in order that the alternatives can be compared.

2.4. Weight assignment

On the basis of a theoretical analysis of twenty weight assignment methods (direct assignment, ordinal methods, comparison on the basis of a single reference, alternative comparison methods, pairwise comparison matrix and others) and on a practical experience in the first round of interviews (Casanovas-Rubio, 2014), the ratio assignment method was chosen. The reasons for selecting this method are that it takes into account ordinal information (information on the preference ranking) as well as cardinal information (how much one criteria is preferred to another criteria) from the decision maker and it does not imply an excessive cognitive workload and time demand for the decision maker. It is the weighting method used in SMART procedure (von

Winterfeldt and Edwards, 1986) and it has been successfully applied to environmental impact assessment of projects such as in Marttunen and Hamalainen (1995). This method consists in assessing the relative importance of each criterion with respect to the least important criterion, taken as reference. It can be said, for example, that a criterion is 2.5 times more important than the least important criterion.

This method was used for assigning the final weights of the tool in a second round of interviews with six panellists representative of the different stakeholders in construction. Table 2 shows the weights obtained as the arithmetic mean of the weights assigned by the experts for different environments: urban, suburban and rural. The standard deviation in the sets of weights assigned by the experts ranges from 0.9 for air pollution in a suburban area to 14.6 for material and energy consumption in an urban area. The average standard deviation is 5.9. The coefficient of variation of the sets of weights ranges from 0.04 for air pollution in a suburban area to 0.54 for noise generation in a rural area. The average coefficient of variation is 0.23. These data reflect the variability in the opinions of the experts interviewed representatives of the different stakeholders in construction. Nevertheless, as explained in section 3.3, the variability in the EII results is low and does not affect the identification of the most environmentally friendly alternative of the case study.

The weights in Table 2 can be used as reference and may be adjusted according to the specific construction environment. The weights of the criteria were assigned considering that the construction work affects one or more sensitive environments apart from unprotected natural areas. When that is not the case, the importance assigned to the criterion effects on sensitive environments should be considerably lower, as the weights within parenthesis reflect.

The definition of the impact tree with its criteria and subcriteria (Fig. 3) aims to include all the environmental impacts. When applying the tool, it is probable that not all the impacts in the tree are produced. When none of the compared alternatives produces the impact of a subcriterion, the subcriterion should be eliminated from the impact tree and, therefore, from the decision making, as it does not help to discriminate between alternatives. For example, if none of the alternatives of the construction process affects the maritime-terrestrial area, this criterion should not be included in the decision. When eliminating a subcriterion from the tree, it is recommended that the weights of the other subcriteria are standardised to total 100 because then:

- the impact of the alternative taken as reference equals 1 when using equation (2),
- the impact of a hypothetical alternative with maximum impact among all the alternatives for each subcriterion equals 1 when using equation (3).

2.5. Definition of indicators

This part of the paper defines an indicator for each subcriterion presented in Fig. 3. The indicators of the proposed tool were developed based on previous research (CIRIA, 2001; Hughes et al., 2011; Trani et al., 2016; and the literature cited in Tables 3-5) and the environmental legislative acts included in Table 1.

Ideally, the indicators should consider information from all the relevant stages in Fig. 2. In practice, it may not be feasible to obtain data for all stages of all indicators. To enable comparison of the alternatives, the indicators for all alternatives must be calculated with data from the same stage or stages. For example, if the energy consumption of all stages is taken into account, it must be taken into account for all the alternatives. Therefore, only the stages of the indicator for which data are known for all or almost all of the alternatives can be included in the calculations. Gangolells et al. (2011) assume a worst-case scenario when data are not available to calculate an indicator, which seems adequate to encourage the collection of data. Under the tool proposed in this paper, the indicator for the alternatives with unknown data should be calculated using the worst-case data from amongst the rest of the alternatives.

Data were gathered and calculated in order to enable and facilitate the calculation of the indicators. Different ways of calculating the data necessary for the calculation of the indicators are defined according to different data availability levels. The more local information that is available, the fewer average values will need to be used and the more accurate the results will be. Some useful data sources are also provided.

As a new approach, the proposed tool integrates various related pieces of data into the same indicator, thereby enabling a more compact and readily applied formulation. For example, the use of recycled materials, certified wood and water was integrated into the material consumption indicator. Table 3 presents the developed indicators and Tables 4 and 5 include some extra data necessary for the calculation of the indicators.

3. Case study

3.1. Introduction

In this section the model is applied to a case study in order to illustrate its practical use. The case study consists in a decision between a precast and a cast-in-place solution for three drains of 50 m each for a residential road (Fig. 4 and 5). The project would be carried out in a suburban area and the land occupation would affect the water resources. No other impact on sensitive environments would be produced by any of the two proposed alternatives. Consequently, the only indicator of effects on sensitive environments useful to discriminate between the two alternatives and used in the comparison is the indicator of effects on water resources.

For the precast alternative as well as for the cast-in-place one, the base of the drains has to be cast-in-place in order to have a better contact with the soil. That requires 39 days of work including 13 days of work of a 5t truck crane to allocate the reinforcing bars plus 13 days of work of a concrete pump truck. For the precast alternative, a self-propelled 12t crane is required to assemble the voussoirs in 6 days. For the cast-in-place alternative, 59 days of work are needed in order to build the vault cast-in-place. These include 31 days of work of a 5t truck crane to assembly the falsework, put in place the reinforcing bars of the arch, and dismantle the falsework; and 13 days of a concrete pump truck. A working day is defined as 8h.

Regarding the transportation of the material, for the precast alternative, five 2h round trips with a 7t truck are necessary to transport the reinforcing bars from the factory to the site plus sixty-one 40 min round trips of a 14 m^3 mixer truck and thirty 6h round trips for the 60 voussoirs with a 24t truck. For the cast-in-place alternative, eight 2h round trips with a 7t truck are needed to transport the steel reinforcing bars and seventy 40 min round trips of a 14 m^3 mixer truck to transport the concrete.

3.2. Results

Table 6 presents the results of the indicators for the precast and cast-in-place alternatives. The air pollution due to manufacture of construction materials includes the particulate matter, NO and SO_2 emitted in the cement plant. All the hazardous waste generated is waste oil (lubricating oil from vehicles and machinery used for the transportation of construction materials and the construction work that becomes unfit for its use).

Table 7 presents the relative environmental impacts and the EII using equation (2) and taking as reference the precast alternative and the cast-in-place alternative respectively and using equation (3) and taking as reference the worst result between the two alternatives for each indicator.

3.3. Discussion of the case study

According to Table 6, the precast alternative is the best regarding noise, waste and hazardous waste generation and effects on water resources, impacts that account for more than 60% of the total weight. The cast-in-place alternative is the best regarding material and energy consumption, GHG emissions and air pollution. The manufacturing and transporting GHG emissions are higher for the precast drains whereas construction emissions are higher for the drains cast-in-place. Total GHG emissions are higher for the precast drains. These results on GHG emissions are consistent with data obtained in Chou and Yeh (2015). Some redesign aspects that could be introduced in order to reduce the EII of the projects are the use of: recycled aggregates, grey and rainfall water, FSC certified timber, low embodied energy materials, energy-efficient vehicles and machinery, local materials, low carbon materials, biofuels and quiet machinery.

The results of Table 7 show that the precast alternative has the lowest EII for the three ways of calculating it and according to the weights assigned by the experts. Therefore, it can be said that, according to EII, the precast alternative is the best in terms of environmental impact. However, the differences between the EII of the precast and cast-in-place alternative are 12%, 2.5% and 6.4% for each of the three ways of calculating it.

The EII concentrates all the environmental impacts of a construction work included in Fig. 3 in a single figure, which may be useful to professionals in construction when selecting the construction process. They can use the EII as another factor to consider in the decision making of construction work together with other relevant factors such as cost and occupational risks. The environmental impact could be considered in the bid evaluation phase, as suggested in Ahn et al. (2013), by means of the EII. The EII could easily be integrated with the Occupational Risk Index presented in Casanovas et al. (2014) for the minimisation of occupational risks in construction.

Two sensitivity analyses have been carried out in order to determine the result stability when changing the weights. The precast alternative has a smaller EII and a smaller impact on water resources, which accounts for a 40.8% of the total weight. The first sensitivity analysis consists in reducing the weight of effects on water resources by intervals of 10% and redistributing it between the other impacts so that the new weights are proportional to the original ones and add up to 100%. The resulting sets of weights (a), (b), (c) and (d) are presented in Table 8. The first sensitivity analysis has been carried out using one equation to simplify (equation (3)). The resulting EIIs of this analysis are presented in Table 9. The second sensitivity analysis has been carried out using the sets of weights (1), (2), (3), (4), (5) and (6) resulting from the weights assigned by the experts interviewed (Table 8). It enables the consideration of the variability in the weights assigned by the experts. The resulting EIIs are presented in Table 10.

Table 9 shows that, as the importance of minimising the effects on water resources decreases (from the original weight set to weight set (d)), the EII of the cast-in-place alternative also decreases, as expected. The change of priorities between the two construction processes regarding the environmental impact happens with the weight set

(c) when the importance of the minimisation of the effects on water resource has been reduced by 30%. None of the experts interviewed assigned such a small weight to that criterion. Therefore, it can be said that the results are stable within the weight range assigned to this criterion by the experts interviewed. As presented in Table 10, the precast alternative is the one with the lowest EII for all the sets of weights assigned by the experts and for the three ways of calculating it (equation (2) with precast and with cast-in-place as reference and equation (3)). These results show that the variability in the weights assigned by the experts does not affect the identification of the most environmentally friendly alternative by using the proposed tool. In fact, the maximum standard deviation in the results of this second sensitivity analysis is 0.02 and the maximum coefficient of variation is 0.02 which shows that the variability in the results is much lower than the variability in the weights.

4. Conclusions

The research presented in this paper provides a new tool especially optimised for quantifying, assessing and comparing the cradle-to-gate environmental impact of different types of construction processes, including structure, infrastructure and building projects. It contributes to quantify the cradle-to-gate environmental impact of construction work, which has been less studied than operational impacts in the life-cycle assessment of buildings. Based on the multi-attribute utility theory and interviews with experts, new criteria, subcriteria, weights and indicators have been defined. The main environmental impacts of construction work have been identified and categorised and their relative importance has been assessed for three different environments: urban, suburban and rural. The proposed weights can be used as reference for other projects and may be adjusted to the specific construction environment. In order to systematise the calculations, a quantitative indicator has been defined for each impact considering different data availability levels.

The generated tool has been tested by analysing two construction alternatives of road drains: one precast and one cast-in-place. The results show that the precast alternative performs better than the cast-in-place regarding noise, waste and hazardous waste generation and has the lowest EII. Two sensitivity analyses have been carried out showing that the results are stable within the weight range assigned by the experts interviewed. In fact, the variability in the results is much lower than the variability in the weights assigned by the experts and does not affect the identification of the most environmentally friendly alternative. Even with a decrease of 20% in the reference weight assigned to water resources, the criterion that could have the greatest influence on the result of the case study, the precast alternative continues being the one with the lowest EII.

The findings enable the environmental impact to be taken into account in decision making related to construction during the design and tender stages and also its monitoring during construction with several practical applications. During the design stage, the tool is useful to compare and rank the environmental impact of different construction alternatives and select the best one in terms of environmental impact. It can help to identify the main environmental impacts, redesign and select preventive measures to be implemented prior to construction. The tool can be of interest to public administrations and other entities. In the tender stage, the tool is useful to compare and prioritise the different construction alternatives proposed by the construction companies in terms of environmental impact, as another aspect to consider in the decision making and selection of the best alternative. It can also be useful to monitor projects during construction, to assess the environmental impact of the work actually carried out and contrast it with the impact predicted at the design stage, enabling corrective measures to be proposed at an appropriate time, in case of deviation. In fact, Barcelona City Council has interest in the tool and, therefore, it is being piloted in the construction projects they promote. The tool can also be helpful for construction companies that want to improve their environmental performance and be at an advantage over their competitors when tendering for the building contracts. They can justify that the construction process they offer is the best among the different construction processes because they have compared the environmental impact by using the tool.

The Environmental Impact Index (EII) presented could be easily used to feed multi-criteria decision-analysis tools together with economic and social aspects, including occupational risks. Apart from occupational risks in construction, studies on other social impacts of construction work are almost inexistent. Therefore, more research is needed to understand and quantify the social impact of construction work, especially in urban areas. This would enable the social dimension to be included in the decision making of construction work. An application software could be developed to accelerate and facilitate the assessment process.

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Table 1. Environmental legislative acts analysed in the research.

European	Spanish	
Directive 87/217/EEC	Spanish Constitution	Royal Decree 679/2006
Directive 92/43/EEC	Royal Decree 849/1986	Law 27/2006
Directive 94/62/EC	Royal Decree 833/1988	Royal Decree 1370/2006
Directive 2000/14/EC	Law 22/1988	Royal Decree 1367/2007
Directive 2001/42/EC	Royal Decree 927/1988	Law 26/2007
Directive 2002/49/EC	Royal Decree 108/1991	Law 34/2007
Directive 2003/4/EC	Royal Decree 1997/1995	Law 42/2007
Directive 2003/35/EC	Law 11/1997	Royal Decree 105/2008
Directive 2003/87/EC	Royal Decree 782/1998	Royal Decree 2090/2008
Directive 2004/35/EC	Royal Legislative Decree 1/2001	Law 41/2010
Directive 2004/42/EC	Order of 7 December 2001	Royal Decree 100/2011
Decision 2005/370/EC	Royal Decree 212/2002	Royal Decree 139/2011
Regulation (EC) No 1907/2006	Royal Decree 117/2003	Law 22/2011
Regulation (EC) No 715/2007	Law 37/2003	Law 2/2013
Directive 2007/46/EC	Royal Decree-Law 5/2004	Law 5/2013
Directive 2008/56/EC	Royal Decree 9/2005	Royal Decree 815/2013
Directive 2008/98/EC	Royal Decree 1513/2005	Law 21/2013
Regulation (EC) No 595/2009	Royal Decree 227/2006	Royal Decree 876/2014
Directive 2009/147/EC	Royal Decree 314/2006	Royal Legislative Decree 1/2016
Directive 2010/75/EU		
Directive 2011/92/EU		

Note: these legislative acts were in force on the 17th of July 2017.

Table 2. Reference weights assigned by the experts to the environmental impacts of construction work for an urban (U), suburban (S) and rural (R) environment.

Criteria	Local weight for criteria (%)			Subcriteria	Local weight for subcriteria (%)			Global weight (%)		
	U	S	R		U	S	R	U	S	R
Resource consumption	20.9 (29.3)	22.5 (32.3)	23.3 (34.6)	Material consumption	49.7	45.8	53.8	10.4 (14.6)	10.3 (14.8)	12.5 (18.6)
				Energy consumption	50.3	54.2	46.2	10.5 (14.7)	12.2 (17.5)	10.8 (16.0)
Pollutants and waste	40.2 (56.5)	36.7 (52.8)	33.3 (49.5)	GHG emissions	19.2	17.8	17.9	7.7 (10.8)	6.5 (9.5)	6.0 (8.8)
				Air pollution	28.1	23.4	17.7	11.3 (15.9)	8.6 (12.3)	5.9 (8.8)
				Noise generation	-	14.1	17.5	-	5.2 (7.4)	5.8 (8.7)
				Waste generation	16.6	15.4	17.2	6.7 (9.4)	5.6 (8.1)	5.7 (8.5)
				Hazardous waste generation	36.1	29.3	29.7	14.5 (20.4)	10.7 (15.5)	9.9 (14.7)
Effects on sensitive environments	38.9 (14.2)	40.8 (14.9)	43.4 (15.9)	Water resources	21.3 (0)	21.5 (0)	21.4 (0)	8.3 (0)	8.8 (0)	9.3 (0)
				Maritime-terrestrial areas	15.2 (0)	15.6 (0)	21.4 (0)	5.9 (0)	6.4 (0)	9.3 (0)
				Protected natural areas	28.6 (0)	27.2 (0)	23.1 (0)	11.1 (0)	11.1 (0)	10.0 (0)
				Threatened taxa	24.5 (0)	24.9 (0)	23.5 (0)	9.5 (0)	10.2 (0)	10.2 (0)
				Unprotected natural areas	10.4 (100)	10.8 (100)	10.6 (100)	4.1 (14.2)	4.4 (14.9)	4.6 (15.9)

Note: The weights within parenthesis are used when the construction work is partially or completely located in an unprotected natural area and does not affect any water resource, maritime-terrestrial area, protected natural area or threatened taxa. A weight has not been assigned to noise generation for an urban area because it is considered that it should be evaluated as a social impact.

Table 3. Indicators of the environmental impact of construction work defined in the model.

Impact	Indicator	Units	Parameter definition
Material consumption	$I_1 = \sum_i \alpha M_i$	kg	i is the construction material or material of an auxiliary element used on site. α is the ratio of material to be counted and takes the values from Table 4. M_i is the mass of the material i. Soil from the earthworks is not considered here; it is implicitly considered in the indicators regarding effects on sensitive environments.
Energy consumption	$I_2 = \sum_i Emat_i + \sum_j Etrans_j + \sum_k Econs_k$	GJ	i is the construction material. j is the construction material transported from the factory to the construction site. k is the machinery or equipment used on site. $Emat_i$ is the energy used in the manufacture of the material i (for new materials, it includes: raw material extraction, transport and manufacture; for recycled or reused materials: extraction, transport and treatment). Material suppliers' data are preferred because they are more realistic. Otherwise they can be obtained from the Inventory of Carbon and Energy (Hammond and Jones, 2011). $Etrans_j$ is the energy used in the transport of the material j. Material suppliers' data are preferred. Otherwise the quantity and type of fuel consumed should be ascertained (based on the distance from the factory to the site, the number of round trips and the vehicle's fuel consumption) and converted into energy units using the gross calorific value from Table 11 from DECC and Defra (2012) – 45.64 and 47.09GJ/t for diesel and petrol

			respectively. $Econs_k$ is the energy used in the machinery, equipment or site facility k. Energy consumption for the machinery and equipment used on site and working hours obtained from the construction project can be used to calculate the energy consumption of the construction work. Energy consumption expressed in type and amount of fuel can be converted into energy units using the gross calorific values from DECC and Defra (2012). If the energy consumption is unknown, the consumption data per hour and kW indicated in SEOPAN (2005) can be used as a reference: diesel, 0.15 – 0.20 litres; petrol, 0.30 – 0.40 litres; and electricity, 0.6 – 0.7 kWh.
GHG emissions	$I_3 = \sum_i Gmat_i + \sum_j Gtrans_j + \sum_k Gcons_k$	$kgCO_2e$	i, j and k are defined in I_2. $Gmat_i$ is the mass of the direct GHG emissions due to the manufacture of material i, including: raw material extraction, transport and manufacture. Material suppliers' data are preferred. Otherwise they can be obtained from the Inventory of Carbon and Energy (Hammond and Jones, 2011). $Gtrans_j$ is the mass of the direct and indirect GHG emissions due to the transport of construction material j. Material suppliers' data are preferred. Otherwise, $Gtrans_j$ can be calculated from the amount and type of fuel used (based on the distance from the factory to the site, the number of round trips and the vehicle's fuel consumption) and the values 3.2413 and 2.7782 $kgCO_2e/l$ for diesel and petrol respectively from Table 1b from DECC and Defra (2012). If the known data include fuel type, vehicle type, transported weight and distance travelled, Tables 7c and 7e from DECC and Defra (2012) can be used. If the freight's mass is

unknown but the distance travelled, vehicle type and fuel type are known, data from Tables 7b and 7d from DECC and Defra (2012) can be used. Table 7f from DECC and Defra (2012) shows emissions due to rail and air freight and Table 7g to maritime freight.

$Gcons_k$ is the mass of the direct and indirect GHG emissions due to use of plant, equipment or facility k. Direct GHG emissions can be obtained by multiplying the emissions of the model by the working time or distance travelled as obtained from the project. If the amount and type of fuel used is known, indirect emissions can be obtained from Table 1b from DECC and Defra (2012). If the plant, equipment, vehicles or installations are powered by electricity and the consumption is known, direct and indirect emissions can be obtained from the factors in Table 10c from DECC and Defra (2012) or updated national data sources. If the model's specific emissions are unknown, total emissions can be estimated by multiplying the consumptions provided in SEOPAN (2005) included in the previous indicator by the total emissions from Table 1b from DECC and Defra (2012), in case of fuel consumption, or Table 10c, in case of electricity consumption. For on-site passenger transport, if the fuel consumption is unknown but the fuel type, distance travelled and vehicle size are known, data from Tables 6b, 6c and 6d from DECC and Defra (2012) can be used to estimate the GHG. If the fuel type is unknown but the vehicle size and distance travelled are known, the values from Table 6e from DECC and Defra (2012) can be used.

Air pollution	$I_4 = \sum_i Amat_i + \sum_j Atrans_j + \sum_k Acons_k$ $Amat_i = P(SO_2 + NO_x + PM_{10} + VOC)_i$ $Atrans_j = Ahgv_j + Algv_j$ Diesel: $Ahgv_j = P(CO + THC + NO_x + PM)_j$ $Algv_j = P(CO + THC + NO_x + PM)_j$ Petrol: $Ahgv_j = P(CO + NMHC + NO_x + PM)_j$ $Algv_j = P(CO + THC + NO_x + PM)_j$	kg	i, j and k are defined in I_2. $Amat_i$ is the air pollution in the manufacture of material i. $P(X)_i$ is the mass of pollutants X emitted in the manufacture of material i. The material suppliers should provide these data. It would be interesting to obtain, at least, the emissions produced in the manufacture of the main construction materials (concrete, steel and asphalt). According to European Union (2010), the industrial activities giving rise to pollution should operate only if they hold a permit which implies the control and monitoring of emissions. Therefore, they should have these data. $Atrans_j$, $Ahgv_j$ and $Algv_j$ are the air pollution in the transport of material j, total, by heavy goods vehicles and by light goods vehicles respectively. $P(X)_j$ is the mass of pollutants X emitted in the transport of the material j. Material suppliers' data are preferred. Otherwise, compulsory emission limits for new vehicles in the EU from Regulations (EC) Nos. 715/2007 and 595/2009 (European Community, 2007b, 2009) can be used as reference. For heavy goods vehicles, the quantity and type of fuel used should be ascertained and converted into emissions using the values from Table 5. For light passenger and commercial vehicles, the vehicle type, fuel type and distance travelled should be ascertained and converted into emissions using the Euro 6 emission limit values from Table 2 of Regulation (EC) No. 715/2007 (European Community, 2007b). Old vehicles have higher emissions but, in future, the renewed stock will be below the limits. THC stands for total hydrocarbons and $NMHC$ for non-methane hydrocarbons.

			$Acons_k$ is the air pollution due to use of the plant, equipment or facility k. Approval under the Directive 2007/46/EC (European Community, 2007a) is optional for mobile machinery and vehicles designed and constructed for use principally on construction sites. Therefore, the emission limits established in Regulation (EC) No. 595/2009 (European Community, 2009) are also optional. Due to the lack of data, this part of the indicator is not used but it is proposed for when more data is available.
Noise generation	$I_5 = \sum_i L_{WAi} \cdot tday_i + 1.2 \sum_i L_{WAi} \cdot tnight_i$	dB·h	i is the equipment for use outdoors, as defined in European Community (2000), used on site. L_{WAi} is the sound power level that can be found in the EC declaration of conformity of the equipment i, according to the European Community (2000). If the L_{WA} is known for most of the equipment, it can be estimated for the rest or average values can be used. $tday_i$ and $tnight_i$ are the operating hours of machine i in the daytime (7:00-23:00) and at night (23:00-7:00) respectively. Operating hours at night are penalised by a factor of 1.2 compared to daytime. This factor was obtained by averaging the rate for daytime and night-time noise quality targets for existing developed areas indicated in Spanish Royal Decree 1367/2007 (Spain, 2007). Other references could be used to define this factor and a different factor could be used for rural environments.
Waste generation	$I_6 = \sum_i Pmat_i + \sum_i Pcons_i$	kg	i is the non-hazardous waste, including waste water that is not going to be reused or recycled. $Pmat_i$ and $Pcons_i$ are the mass of non-hazardous waste i produced in the manufacture of construction materials and in the construction work respectively.

Hazardous waste generation	$I_7 = \sum_i Phmat_i + \sum_i Phtrans_i + \sum_i Phcons_i$	kg or l (if oil is the only hazardous waste)	i is the hazardous waste (a waste with the properties included in Annex III of Directive 2008/98/EC (European Community, 2008)). Some hazardous wastes in construction are asbestos, waste oil and explosives. $Phmat_i$, $Phtrans_i$ and $Phcons_i$ are the mass of the hazardous waste i produced in the materials' manufacture, transport, and construction work respectively, excluding waste oils that are going to be regenerated. If the amount of waste oil is unknown, the following approximation of oil consumption as a percentage of the cost of the plant's fuel consumption can be used (SEOPAN, 2005): diesel engine, 20%; petrol engine, 10%; and electric power, 5%.
Water resources	$I_8 = \sum_i Sw_i \cdot t_i$	m^2·day	i is the construction work stage with a markedly different land occupation. Sw_i is the ground surface of water resources plus ground surface of the area within 100 metres of the riverbed, measured horizontally, occupied by the construction work in the construction work stage i. t_i is the duration of stage i. Water resources include: continental waters, continuous or discontinuous natural watercourses, lakes, lagoons, surface dams in public riverbeds and underground aquifers.
Maritime-terrestrial areas	$I_9 = \sum_i Smar_i \cdot t_i$	m^2·day	i and t_i are defined in I_8. $Smar_i$ is the ground surface of maritime-terrestrial area plus ground surface of the area extending 100 metres inland, as measured from the inner limit of the seashore, occupied by the construction work during the stage i.

			Maritime-terrestrial areas include, among others: seashores and ria shores, territorial seas and their islets, internal waters and their islets, and natural resources on the continental shelf.
Protected natural areas	$I_{10} = \sum_i Sprot_i \cdot t_i$	m^2·day	i and t_i are defined in I_8. $Sprot_i$ is the ground surface of protected natural areas, Natura 2000 areas and other protected areas occupied by the construction work during stage i.
Threatened taxa	$I_{11} = \sum_j (Nvul + 2 \cdot Nend + 3 \cdot Ncrit)_j \cdot t_j$	day	j is the construction stage with a markedly different impact on threatened taxa. $Nvul$, $Nend$ and $Ncrit$ are the number of vulnerable, endangered and critically endangered taxa respectively (IUCN Standards and Petitions Subcommittee, 2014). $(\ \ )_j$ are the taxa that can be affected during stage j of the construction work. t_j is the duration of stage j.
Unprotected natural areas	$I_{12} = \sum_i Snat_i \cdot t_i$	m^2·day	i and t_i are defined in I_8. $Snat_i$ is the area of unprotected natural ground surface affected by stage i.

Table 4. Data for I_1: Reference values of α depending on the material type.

Material type	α
New construction materials and clean water	1
Reusable auxiliary elements. Where n is the number of times used on site and n_T the total number of uses over the element's lifetime	$\frac{n}{n_T}$
Recycled or reused construction materials, FSC-certified wood and grey and rainfall water reused on site[a]	0

[a] α could be defined differently according to the material's local or global availability, capacity for renewal and current recycling rate. As construction material recycling rates are low in Spain – 14% according to the European Commission (DG ENV) (2011) – this indicator does not count the consumption of reused and recycled material (α=0).

Table 5. Data for I_4: some emission limits for heavy goods vehicles (Euro VI) converted to grams per litre of fuel consumed (DECC and Defra, 2012; European Community, 2009; and authors' calculations).

	Limit values (g/l)				
Fuel type	CO	THC	NMHC	NO_x	PM
Diesel	42.586	1.703	-	4.897	0.106
Petrol	38.470	-	1.539	4.424	0.096

Note: The regulation also limits methane emissions but they were not included in the indicator I_4 because they are already considered in I_3.

Table 6. Indicators of environmental impact calculated for the precast and cast-in-place drains.

Impact	Stage	Results of the indicators		
		Precast	Cast-in-place	Units
Material consumption	Construction work	2747029.20	2284411.50	kg
Energy consumption	Construction materials	4998.84	3908.77	GJ
	Transportation of construction materials	215.31	59.88	GJ
	Construction work	261.56	625.95	GJ
	Total	5475.71	4594.61	GJ
GHG emissions	Construction materials	557934.04	435836.55	$KgCO_2e$
	Transportation of construction materials	19372.65	5387.93	$KgCO_2e$
	Construction work	23533.94	56320.22	$KgCO_2e$
	Total	600840.63	497544.70	$KgCO_2e$
Air pollution	Construction materials	436.55	362.34	kg
	Transportation of construction materials	276.91	77.02	kg
	Total	713.46	439.36	kg
Noise generation	Construction work	25152.00	55776.00	dB·h
Waste generation	Construction work	212206.92	226010.93	kg
Hazardous waste generation	Transport	269.45	74.94	l
	Construction work	327.32	783.33	l
	Total	596.77	858.27	l
Water resources	Construction work	14100	17100	m^2·day

Table 7. Environmental Impact Indexes for the precast and cast-in-place drains calculated with equations (2) and (3).

		Relative environmental impacts and EII					
		Equation (2) precast as reference		Equation (2) cast-in-place as reference		Equation (3) the alternative with the greatest impact as reference	
Subcriteria	Global weights (%)	Precast	Cast-in-place	Precast	Cast-in-place	Precast	Cast-in-place
Material consumption	10.3	1.000	0.832	1.203	1.000	1.000	0.832
Energy consumption	12.2	1.000	0.839	1.192	1.000	1.000	0.839
GHG emissions	6.5	1.000	0.828	1.208	1.000	1.000	0.828
Air pollution	8.6	1.000	0.616	1.624	1.000	1.000	0.616
Noise generation	5.2	1.000	2.218	0.451	1.000	0.451	1.000
Waste generation	5.6	1.000	1.065	0.939	1.000	0.939	1.000
Hazardous waste generation	10.8	1.000	1.438	0.695	1.000	0.695	1.000
Water resources	40.8	1.000	1.213	0.825	1.000	0.825	1.000
EII		1.000	1.120	0.975	1.000	0.864	0.919

Table 8. Sets of weights used for the two sensitivity analyses.

	Weight set										
		Sensitivity analysis 1				Sensitivity analysis 2					
Subcriteria	Original	(a)	(b)	(c)	(d)	(1)	(2)	(3)	(4)	(5)	(6)
Material consumption	10.3	12.0	13.8	15.5	17.3	11.1	12.8	8.4	9.5	4.2	18.0
Energy consumption	12.2	14.3	16.3	18.4	20.4	11.1	12.8	8.4	14.3	12.5	12.0
GHG emissions	6.5	7.6	8.7	9.8	10.9	8.5	7.8	5.9	7.4	5.6	4.6
Air pollution	8.6	10.1	11.5	13.0	14.4	10.1	9.8	7.8	8.4	8.3	6.9
Noise generation	5.2	6.1	7.0	7.8	8.7	5.7	7.8	3.9	6.4	5.5	2.3
Waste generation	5.6	6.5	7.5	8.4	9.4	6.2	3.9	7.8	5.3	2.8	6.9
Hazardous waste generation	10.8	12.6	14.4	16.3	18.1	14.0	11.8	7.8	10.6	11.1	9.3
Water resources	**40.8**	**30.8**	**20.8**	**10.8**	**0.8**	33.3	33.3	50.0	38.1	50.0	40.0
Total	100	100	100	100	100	100	100	100	100	100	100

Table 9. EIIs for the precast and cast-in-place drains resulting from the first sensitivity analysis using equation (3).

	EII				
	Weight set				
Construction process	Original	(a)	(b)	(c)	(d)
Precast	**0.864**	**0.870**	**0.877**	0.883	0.890
Cast-in-place	0.919	0.905	0.891	**0.877**	**0.864**

Table 10. EIIs for the precast and cast-in-place drains resulting from the second sensitivity analysis considering the variability in the weights assigned by the experts.

Equation used	Construction process	EII						
		Weight set						
		Original	(1)	(2)	(3)	(4)	(5)	(6)
Equation (2) precast as reference	Precast	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**
	Cast-in-place	1.120	1.116	1.127	1.125	1.125	1.155	1.074
Equation (2) cast-in-place as reference	Precast	**0.975**	**0.988**	**0.988**	**0.956**	**0.977**	**0.942**	**0.997**
	Cast-in-place	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Equation (3)	Precast	**0.864**	**0.864**	**0.860**	**0.862**	**0.862**	**0.847**	**0.885**
	Cast-in-place	0.919	0.910	0.907	0.932	0.916	0.931	0.916

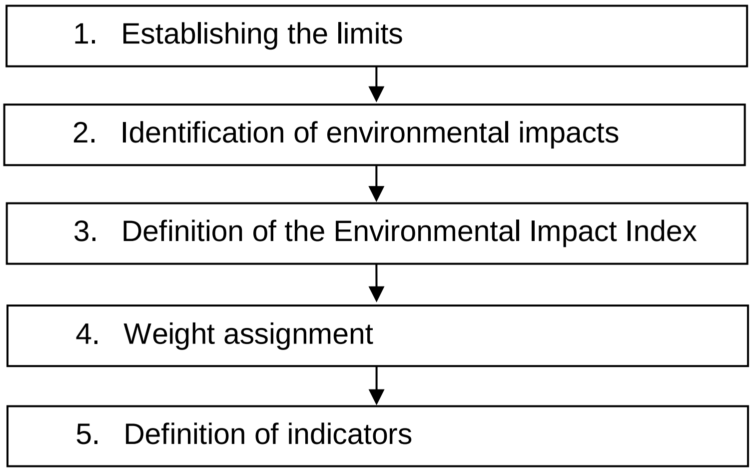

Figure 1. The main steps followed to develop the environmental impact model.

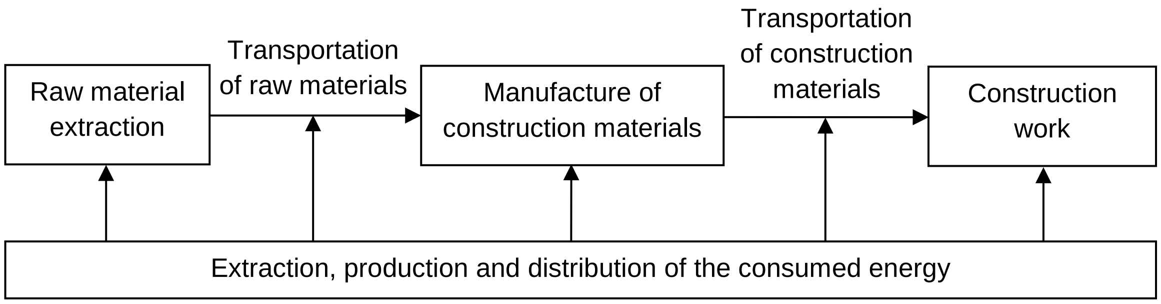

Figure 2. Cradle-to-gate stages in construction considered by the model.

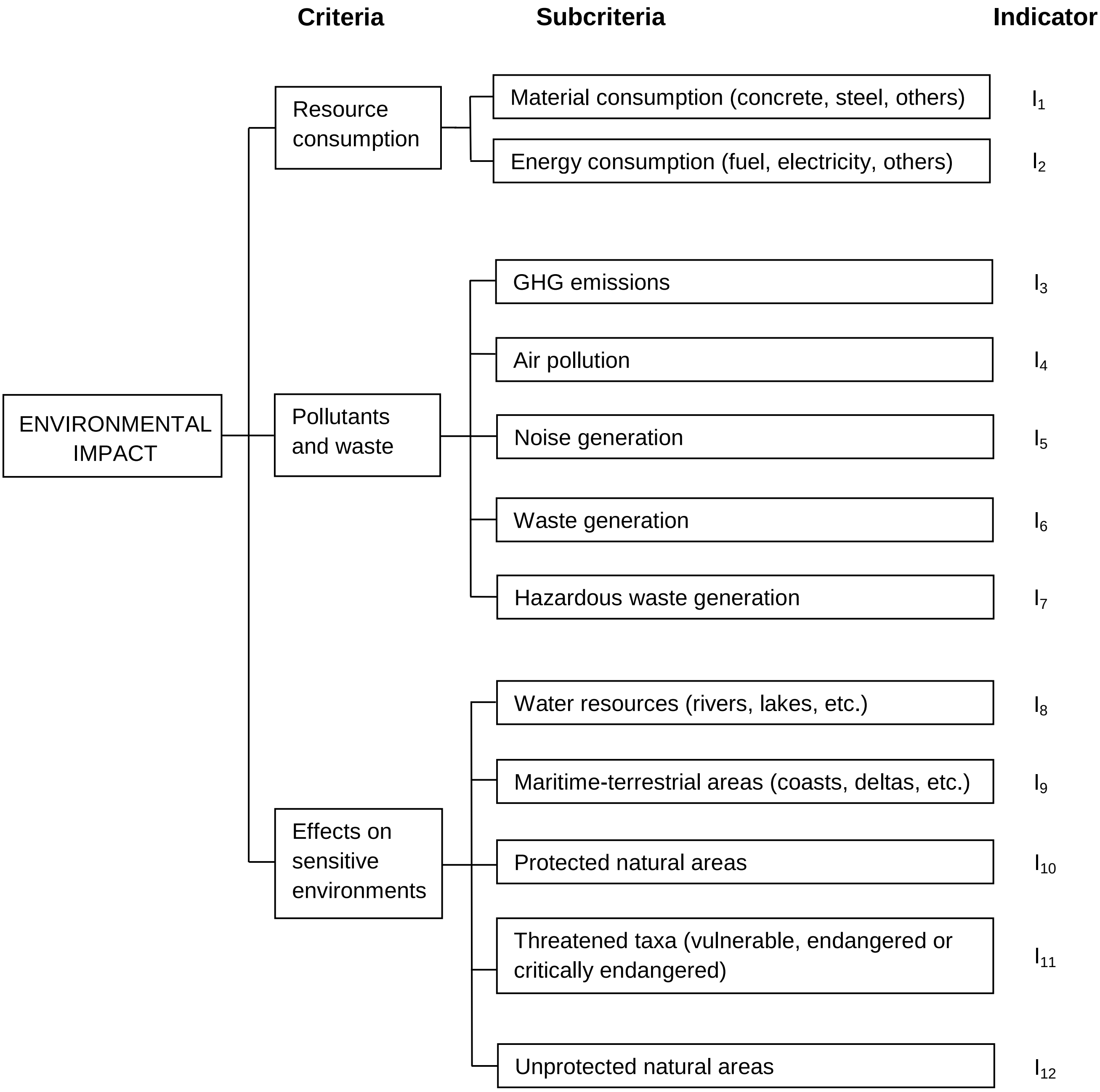

Figure 3. Impact tree with the environmental impacts caused by construction work.

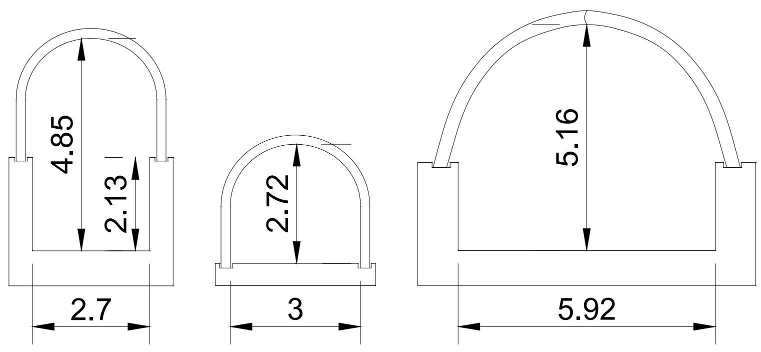

Figure 4. Drains with precast concrete arch analysed in the case study.

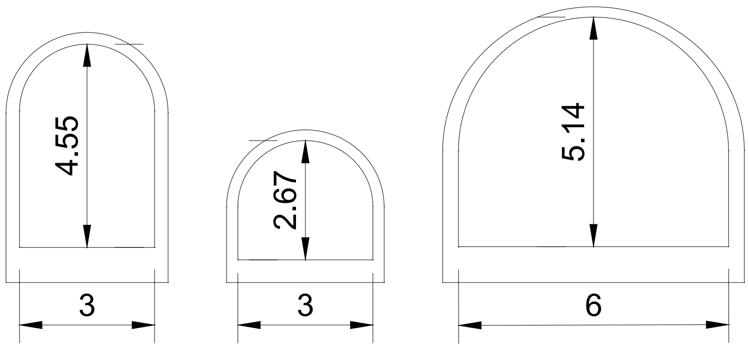

Figure 5. Drains with cast-in-place concrete arch analysed in the case study.