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Inclusion of prevention scenarios in LCA of construction waste management

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Abstract

Purpose Life-Cycle Assessment (LCA) has been applied extensively for the environmental evaluation of solid waste management. However, there is a lack of approaches based on the LCA perspective to deal with waste prevention, which constitutes the first and overriding principle of waste management hierarchy, both in relation to solid waste in general and to construction waste (CW) in particular. This paper explores the possibilities of the LCA for the evaluation of CW management that include prevention activities.

Methods The functional unit and system boundaries used in the traditional LCA of CW management are redefined to include prevention scenarios; this leads to two methodological options (Options 1 and 2). From the above, general and simplified models were developed to compare non-prevention with prevention scenarios. The general model evaluates CW management scenarios that consider several CW fractions, while the simplified model is applicable to the analysis of one separated CW fraction. A case study was carried out on new buildings in Spain. Optimization and replacement measures of prevention were developed and four CW management scenarios were compared using the general model. The simplified model was applied to the management of 1 tonne of concrete waste.

Results and discussion The impact category of climate change was evaluated. Prevention was the most favourable scenario, since, in addition to reducing the amount of CW generated it also reduced CO_2 emissions. Regarding the usefulness of each methodological option, Option 1 is more suitable for those LCAs that are aimed towards helping in the decision-making process regarding preventive measures during the design phase, as it enables the actual impact of CW to be monitored in construction work, a building element, or a separate fraction. However, Option 2 facilitates the interpretation of those loads saved by means of not generating CW in prevention scenarios, and this option is hence more useful in LCAs whose objective is the selection of the optimal type of CW management.

Conclusions Most CW prevention studies in the reviewed literature are focused on the reduction of the quantities of waste. The methodological approaches in this study allow a greater insight into the effects of prevented CW on the environment. The proposed models could support the preparation of national waste programs, and could serve as an instrumental tool to simulate the environmental impacts of CW management scenarios that include waste prevention.

Keywords: Life-Cycle Assessment; Construction waste; Waste management scenarios; Waste prevention activities; Waste hierarchy.

1. Introduction

Construction and demolition waste (CDW) management represents a serious environmental problem in many countries mainly due to the large volume of CDW generated (Banias et al. 2011), the low level of recovery (JRC-IES 2011), and the lack of waste prevention (Poon 2007; Osmani et al. 2008; Llatas and Osmani 2016). In the United States, for example, CDW represents more than twice the amount of generated municipal solid waste (EPA 2013); in the UK, CDW equates to three times the combined waste produced by all households (DEFRA 2007); and in Hong Kong in 2013, mixed CDW accounted for about 25% of the total waste dumped at the three existing landfills, which warned the government that the lack of measures for the reduction of CDW represents a huge problem for the lifespan of the landfills (EPD 2013). In the EU-28, CDW is the heaviest and most voluminous waste stream, and is responsible for 34% of total waste generation (Eurostat 2013). Furthermore, CDW production grew at an average rate of 45% in the period 2004–2012, unlike other waste streams, whose production levels were maintained constant (households) or even decreased (manufacturing, mining and quarrying, agriculture, forestry and fishing) (Eurostat 2015). However, despite its high potential for recycling and re-use, CDW recycling rates of some EU member states remain below acceptable levels (Tojo and Fischer 2011), such those in Cyprus, Greece and Finland, with rates as low as 10% of the overall landfilled waste (European Commission 2011). To deal with this issue, the EU Waste Framework Directive (European Commission 2008) stipulates that Member States must take the necessary measures designed to achieve that, by 2020, a minimum of 70% (by weight) of non-hazardous CDW excluding naturally occurring material is be prepared for re-use, recycling or undergo other material recovery. Moreover, this directive establishes that prevention is the most favourable management option in the waste management hierarchy, and highlights the need to consider the whole life-cycle of products and materials in order to minimize their environmental impacts.

Life-Cycle Assessment (LCA) is a tool to assess the potential environmental impacts throughout a product's life-cycle (ISO 2006a)(ISO 2006a). This method has been widely used to evaluate the environmental performance of solid waste management, and in particular, that of household waste. However, although in recent decades researchers have shown an increased interest in CDW (Lu and Yuan 2011), LCA applications to the management of this waste stream have been limited (Ortiz et al. 2010; Mercante et al. 2012; Laurent et al. 2014). Moreover, there is a lack of approaches based on the LCA perspective to deal with prevention activities, both in relation to solid waste in general and to CDW in particular. As such, Laurent et al. (2014) acknowledged "in terms of technological coverage, the literature has largely overlooked the application of LCA to waste prevention activities and to relevant waste types apart from household waste, e.g. construction and demolition waste. Waste management practitioners are thus encouraged to bridge these gaps in future applications of LCA".

On this basis, and in order to address this gap in the literature, this article explores the possibilities of LCA methodology for the evaluation of construction waste (CW) management scenarios that include waste prevention activities. A review of LCA applied to prevention scenarios highlights the lack of studies in the field of CW and the limitations of the traditional LCA methodology to incorporate prevention activities. A general model is developed from the adjustments of the traditional LCA methodology and a simplified model is proposed to facilitate the evaluation of a separate CW fraction whose management includes prevention.

Finally, a case study of new buildings in Spain is included as an illustration of the model approaches. Four CW management scenarios were compared, with the inclusion of a prevention scenario. It is expected that the methodological approaches in this study represent a breakthrough in the traditional models of LCA in CW management.

2 Review of LCA applied to CW prevention activities and limitations

2.1 Methodological approaches of traditional LCA applied to CW management

The LCA method is based on the quantification of environmental impacts of a product throughout its life-cycle, from "cradle to grave" (ISO 2006a; ISO 2006b). In general terms, ISO 14040 standards establish four stages for LCA application: Goal and scope definition, life-cycle inventory analysis (LCI), life-cycle impact assessment (LCIA), and interpretation. The LCA approach adapted to buildings is defined in EN 15978 (CEN 2011), which represents a methodological guide for the quantification of environmental impacts of buildings. According to EN 15978, four phases (A1-3 to C1.4) are distinguished in the full life-cycle of a building, which are further subdivided into modules, with the additional information beyond the life-cycle of the building (D), as shown in Figure 1.

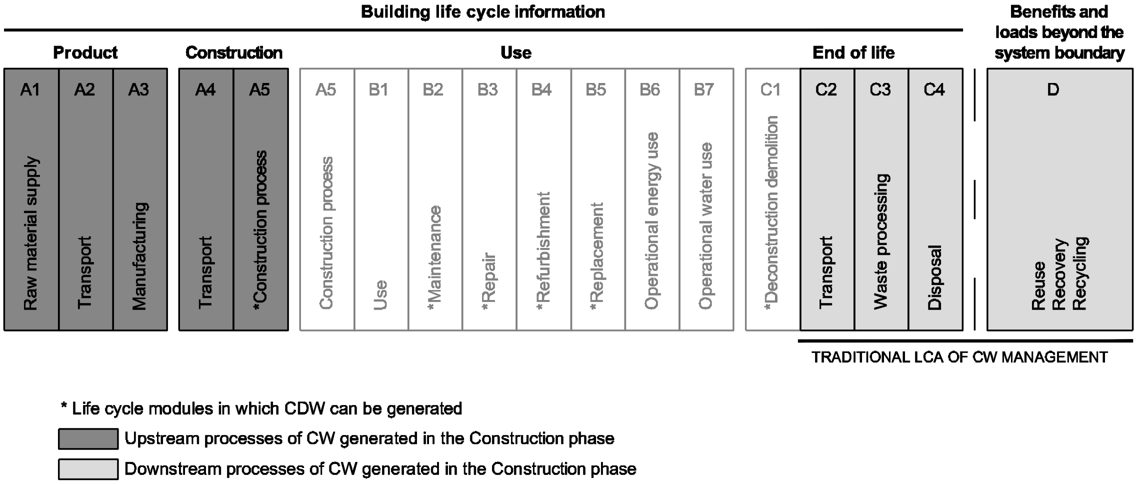


Fig. 1. Phases and modules to perform a construction waste (CW) management LCA in buildings according to EN 15978. Upstream and downstream processes in the construction phase.

Within the life-cycle of a building, CDW can be generated in the following modules: Construction (A5), Maintenance (B2), Repair (B3), Refurbishment (B4), Replacement (B5), and Demolition (C1). Processes and activities that occur before the generation of CDW are called upstream processes, for example, upstream processes of CW generated in the Construction module (A5) would include product (A1-3) and construction (A4-5) processes. On the other hand, downstream processes take place once CW has been generated. These are associated with waste management and, depending on the system boundaries selected, may be comprised of: Transport (C2), Waste processing (C3), Disposal (C4), and prevented impacts from virgin production. Within the methodological approaches of traditional LCA models applied to CW management, the same amount of CW is usually compared under various management scenarios and the 'zero burden assumption' is generally applied. This assumption affects the system boundaries and the functional unit. On the one hand, the upstream processes are excluded from the system boundaries since they are common to all scenarios. On the other hand, the 'zero burden assumption' is only applicable if the amount of CW to compare is identical in all scenarios (Ekvall et al. 2007).

In the literature review on LCA applied to CDW management, the studies compare different management scenarios or quantify the environmental benefits of a certain management strategy. Eleven relevant studies have been compiled from the literature and included in Table 1, which shows the functional unit used, the system boundaries, and the scenarios assessed in each case.

Table 1
Functional unit, types of CW composition evaluated, stages of the system boundaries, and scenarios assessed in studies of application of the traditional LCA methodology to construction waste (CW)

Study	**Functional unit**	**Types of CW composition**	**System boundary stages**	**Scenarios assessed**	
				Non-prevention	**Prevention**
Craighill and Powell (1999)	1 tonne separated CW	Analysis by fractions	End of life[c]	Recycling Disposal	No
Balazs et al. (2001)	Total tonnes of CW	Specific composition[a]	End of life	Reuse Recycling Disposal	No
Grant and James (2005)	1 tonne separated CW	Analysis by fractions	End of life[c]	Recycling	No
Rivela et al. (2006)	Other	Analysis by fractions	End of life[c]	Recycling Incineration	No
Blengini (2009)	m^2 built area	Specific composition[a]	Product Construction Use End of life	Recycling Disposal	No
DECCW (2010)	1 tonne separated CW	Analysis by fractions	End of life[c]	Recycling	No
Ortiz et al. (2010)	Total amount kg/m^2	Generic Composition	End of life[c]	Recycling Incineration	No

	1 tonne separated CW	Analysis by fractions		Disposal	
Blengini and Garbarino (2010)	1 tonne mixed CW	Generic composition[b]	End of life[c]	Recycling	No
Mercante et al. (2012)	1 tonne mixed CW	Generic composition[b]	End of life[c]	Recycling	No
Martínez et al. (2013)	m2 built area	Specific composition[a]	End of life	Reuse/Recycling Disposal	No
Butera et al. (2015)	1 tonne separated CW	Analysis by fractions	End of life[c]	Recycling Disposal	No

a. CW composition in a specific building
b. CW composition obtained from general data: regulations or recycling plants
c. Demolition processes not included

Regarding the system boundaries, the upstream processes are excluded, since the 'zero burden assumption' is applied. Exceptions include: Balazs et al. (2001), and Martínez et al. (2013), which involve demolition processes since CDW management scenarios are compared along with various demolition models; and Blengini (2009) which assesses the complete life-cycle of a building, and compares different CDW management options. With respect to the functional unit, several studies analyse the management of a given amount (set at 1 tonne in all cases) of a certain CDW fraction (separate or mixed) (Craighill and Powell 1999; Grant and James 2005; DECCW 2010; Ortiz et al. 2010; Butera et al. 2015) or the management of the total quantity of CDW generated on a specific construction site (Balazs et al. 2001; Ortiz et al. 2010); in other cases, the functional unit is related to the built area of the building under study (Blengini 2009; Martínez et al. 2013). As the defined functional units reflect, these studies analyse a generic waste composition obtained from official data, or they study a specific composition of waste generated on a specific construction project, or they perform an analysis by fractions. Another issue to point out is that all the studies evaluate non-prevention scenarios which consider recycling treatments: in many cases comparing them with other management options, such as disposal, incineration, or even reutilization. However, none of these studies consider prevention scenarios.

2.2 CW prevention scenarios and LCA

Under the EU Waste Framework Directive (European Commission 2008), *'Prevention'* is the highest priority according to the Waste Hierarchy and is defined as *"measures taken before a substance, material or product has become waste, that reduce: (a) the quantity of waste, including through the use of products or the extension of the life span of products; (b) the adverse impacts of the generated waste on the environment and human health; or (c) the content of harmful substances in materials and products"*. According to this definition, prevention includes both the reduction of the amount and the degree of toxicity of the CDW generated and the reduction of the adverse environmental impacts. However, in the literature a greater effort is exerted on studying the causes and strategies for reducing the amounts of CDW (Skoyles and Skoyles 1987; Poon et al. 2004; Jaillon et al. 2009) rather than on studying the effects on the environment of the prevented CW.

The literature on CW recognizes the importance of the design phase in achieving waste reduction on construction sites (Ekanayake and Ofori 2004; Innes 2004; Baldwin et al. 2006; Osmani et al. 2008; Llatas and Osmani 2016). Several prevention activities and strategies have been identified in recent decades. Examples include: the modulation of the project and dimensional coherence of products (Coventry and Guthrie 1998), the optimization of structural solutions (Greenwood 2003), the standardization of design applied to both the use of standard dimensions and units (Hylands 2004), the use of reclaimed CW (Gibb 2001; Kartam et al. 2004) and the use of cleaner technologies, such as pre-casting and prefabrication (Dainty and Brooke 2004; Baldwin et al. 2006). These strategies represent CW prevention activities that, under the LCA perspective, can be classified into two types of measures.

- *Optimization measures*, whereby the components of the building elements are optimized, and the amount of the CW generated is therefore reduced. In these cases, there is no variation of the CW composition (e.g. the use of modular coordination among building elements).
- *Replacement measures*, whereby the building elements are replaced by other building elements that are without toxic materials or that generate less waste. In these cases, the amount of CW generated can be reduced and there is a variation of the CW composition (e.g. the use of prefabricated elements instead of elements executed on-site).

Therefore, optimization measures can prevent impacts associated with the whole life-cycle of the reduction in the products and materials, from both CW management processes and from processes prior to CW generation. However, in the case of replacement measures, the impacts associated with the whole life-cycle of the replaced building element are prevented, although additional impacts associated with the whole life-cycle of the alternative replacement products must be considered, as shown in earlier studies (JRC-IES 2011; Nessi et al. 2013).

2.3 Limitations of traditional LCA of waste management applied to CW prevention scenarios

Ekvall et al. (2007) and Nessi et al. (2013) reported that traditional LCA applied to waste management fails to allow the consideration of prevention scenarios. The inclusion of a prevention scenario in the assessment implies that the amount and even the composition of waste cease to be the same in all scenarios; therefore, the ‘zero burden assumption’ is no longer valid. This affects two methodological aspects: the system boundaries and the functional unit. On the one hand, the system boundaries must include the processes prior to the CW generation. On the other hand, the functional unit must allow the comparison of different quantities and compositions of CW.

Another limitation of this approach is that the impacts of the scenario that generates the least waste are often overestimated. If the ‘zero burden assumption’ is applied, then the upstream processes of prevention and non-prevention scenarios are considered identical to the upstream processes of non-prevention scenarios, instead of including the appropriate processes in each scenario (Finnveden 1999; Nessi et al. 2013). Furthermore, the application of the ‘substitution by system expansion’ method (as a method to solve the allocation problem of recovery processes (Finnveden et al. 2009)) may cause negative impact indicators, and this could lead to the paradoxical conclusion that the smaller the amount of waste generated, the smaller the environmental benefits obtained (Nessi et al. 2013).

Despite these limitations, the literature review reveals that there are insufficient approaches based on LCA to address prevention activities in CW management. Even in the field of household waste management, research studies have paid far too little attention to this issue (Cleary 2010; Gentil et al. 2011; Nessi et al. 2013).

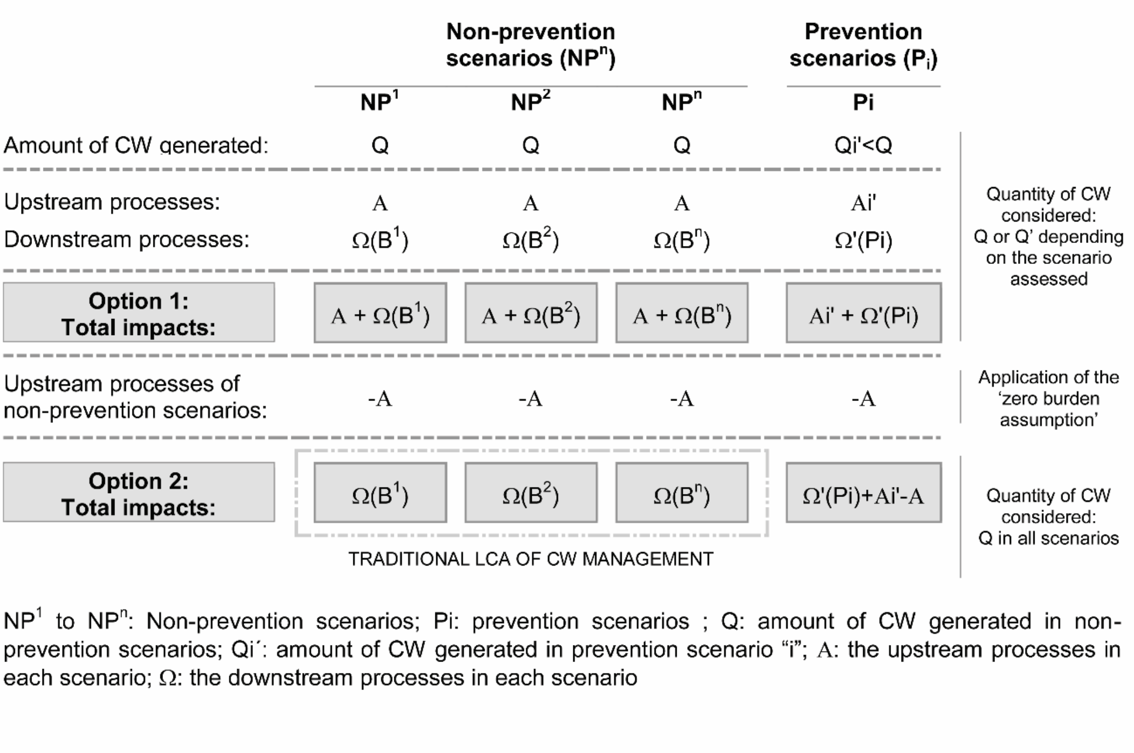
3 Methodological proposal based on LCA to evaluate CW prevention scenarios

3.1 Adjustments to the traditional LCA applied to waste management

This study focuses on construction waste (CW) that is generated during the construction stage of the life-cycle of a building: the A4-5 stage as shown in Figure 1. The method evaluates two groups of CW management scenarios that are defined within the context of this research:

- *Prevention scenarios (Pi)* are those scenarios that reduce the amount of CW generated at source by applying prevention activities, such as optimization and replacement measures.
- *Non-prevention scenarios (NP^n)* are those scenarios that do not reduce the amount of CW generated at source and consider other waste management options once the CW has been generated, such as preparing for reuse, recycling, other recovery (e.g. incineration), and disposal.

Two types of processes can be distinguished: the upstream processes (those occurring during the production and construction stages) and the downstream processes (those related to the management of CW, once generated). From the limitations detected in the traditional methodology, a number of adjustments are proposed in order to allow the comparison of non-prevention scenarios with prevention scenarios. Similar to Nessi et al. (2013), the proposed adjustments lead to two options, whose methodological characteristics are studied within the framework of building construction. Figure 2 shows the basis of the development of the proposed methodological options, which mainly consists of the treatment of two issues: a) The different amounts of CW generated between non-prevention scenarios (Q) and prevention scenarios (Qi'); and b) the need to take into account both the upstream processes (A) and the downstream processes (Ω).



	Non-prevention scenarios (NP^n)			**Prevention scenarios (P_i)**	
	NP^1	**NP^2**	**NP^n**	**Pi**	
Amount of CW generated:	Q	Q	Q	Qi'<Q	
Upstream processes:	A	A	A	Ai'	Quantity of CW considered: Q or Q' depending on the scenario assessed
Downstream processes:	$\Omega(B^1)$	$\Omega(B^2)$	$\Omega(B^n)$	$\Omega'(Pi)$	
Option 1: Total impacts:	$A + \Omega(B^1)$	$A + \Omega(B^2)$	$A + \Omega(B^n)$	$Ai' + \Omega'(Pi)$	
Upstream processes of non-prevention scenarios:	-A	-A	-A	-A	Application of the 'zero burden assumption'
Option 2: Total impacts:	$\Omega(B^1)$	$\Omega(B^2)$	$\Omega(B^n)$	$\Omega'(Pi)+Ai'-A$	Quantity of CW considered: Q in all scenarios
	TRADITIONAL LCA OF CW MANAGEMENT				

NP^1 to NP^n: Non-prevention scenarios; Pi: prevention scenarios ; Q: amount of CW generated in non-prevention scenarios; Qi´: amount of CW generated in prevention scenario "i"; A: the upstream processes in each scenario; Ω: the downstream processes in each scenario

Fig. 2. Methodological options proposed for the inclusion of prevention scenarios (P_i) in the traditional LCA of CW management of non-prevention (NP^n) scenarios.

In Option 1, in each scenario, the actual CW generated is considered; whereby, CW amounts in non-prevention scenarios (Q) are distinguished from CW amounts in prevention scenarios (Qi'). At the same time, in each scenario, the appropriate upstream and downstream processes are taken into account, thereby obtaining the actual impacts of each scenario. In Option 2, CW generated in non-prevention scenarios (Q) is evaluated in all scenarios and, in this case, prevention is considered as another waste management option to be applied to the corresponding CW generated in prevention scenarios. In this methodological option, the ‘zero burden assumption’ is considered, whereby the upstream processes belonging to non-prevention scenarios are removed from all scenarios. In non-prevention scenarios, since the upstream processes are identical, only the appropriate downstream processes are taken into account, which results in similar scenarios to those of the traditional methodology. However, the upstream processes differ in the CW prevention scenarios, and hence, in these scenarios, the actual upstream and downstream processes minus the upstream processes of non-prevention scenarios are taken into account.

From the above, the general model and the simplified model were developed. The general model is relevant in the evaluation of management scenarios in which various CW fractions are generated, as occurs in the execution of a building element or in construction work. The simplified model is applicable to the analysis of a given amount of a certain type of managed CW, and enables a comparison to be made, for example, of the impacts associated to ‘1 tonne of each separate CW’ that has been generated or prevented.

3.2 General model approach

3.2.1 Functional unit

In Option 1, the amount of CW managed can differ in each scenario; however, with Option 2, it must be identical in all scenarios and equal to the maximum amount of CW generated in a non-prevention scenario. This issue affects the functional unit which, under Option 1, is defined as: “*the management of the actual amount of CW generated in each scenario, with or without prevention activities*” and, according to Option 2, the functional unit is defined as: “*the management of the CW generated in a scenario without prevention activities”.*

3.2.2 System boundaries

In Option 1, the downstream and upstream processes are included in each scenario. Using Option 2, the downstream processes are included in all scenarios, but the upstream processes are only taken into account in prevention scenarios. With both options, the processes associated with the use and the demolition stages are excluded from the system boundaries, since, in construction work, CW is generated during the construction process stage. Figure 3 illustrates the life-cycle modules included in the system boundaries depending on each methodological Option.

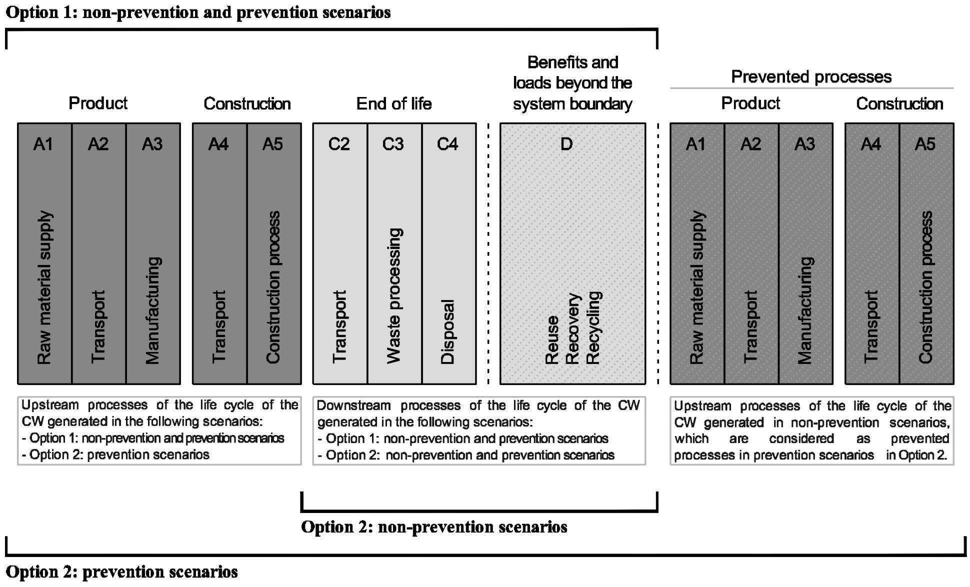


Fig. 3. System boundaries in each methodological option and scenario assessed according to EN 15978

3.2.3 Quantification of environmental impacts

The environmental impacts associated to prevention (P_i) and non-prevention (NP^n) scenarios are calculated by applying equations 1-4. These equations allow the analysis of scenarios that consider the two types of prevention activities (optimization and replacement measures), since they take into account variations in both the amount and composition of the CW managed.

1. $X_1^{\,j} = \sum_i^n \alpha_i^{\,j} \cdot q_i + \sum_i^n \omega_i^{\,j} \cdot q_i$

2. $X_{P1}^{\,j} = \sum_i^n \alpha_i^{\,j} \cdot q'_i + \sum_i^n \omega_i^{\,j} \cdot q'_i$

3. $X_2^{\,j} = \sum_i^n \omega_i^{\,j} \cdot q_i$

4. $X_{P2}^{\,j} = \sum_i^n \alpha_i^{\,j} \cdot (q'_i - q_i) + \sum_i^n \omega_i^{\,j} \cdot q'_i$

- $X_1^{\,j}$ is the impact ‘j’ of a non-prevention scenario (NP^n) in Option 1.
- $X_{P1}^{\,j}$ is the impact ‘j’ of a prevention scenario (P_i), in Option 1.
- $X_2^{\,j}$ is the impact ‘j’ of a non-prevention scenario (NP^n) in Option 2.
- $X_{P2}^{\,j}$ is the impact ‘j’ of a prevention scenario (P_i), in Option 2.

- ω_i^j is the impact ‘j’ associated to the downstream processes of 1 tonne of the fraction ‘i’ of generated CW.
- α_i^j is the impact ‘j’ associated to the upstream processes of 1 tonne of the fraction ‘i’ of generated CW.
- q_i is the quantity in tonnes of the fraction ‘i’ of CW generated on-site without applying prevention measures in a non-prevention scenario (NP^n)
- q'_i is the quantity in tonnes of the fraction ‘i’ of CW generated on-site by applying prevention measures in a prevention scenario (P_i).

3.3 Simplified model approach

The analysis of a given amount of a specific type of CW that has been managed or prevented, such as ‘1 tonne’, may be of interest in certain cases, and hence this simplified model is developed. This analysis would allow, for example, simplifications in the environmental impact calculations in the case that all the CW generated in non-prevention scenarios ‘NP^n’ would be reduced in a prevention scenario ‘P_0’. Hence, the actual amount of CW generated in each scenario would be: 1 tonne of the CW fraction ‘i’ in non-prevention scenarios ‘NP^n’, and 0 tonnes in prevention scenario ‘P_0’.

Therefore, in Option 1, the functional unit is defined as: “*the management of the actual amount of CW generated in each scenario, which is 1 tonne of the CW fraction “i" in non-prevention scenarios ‘NP^n’, and 0 tonnes in prevention scenario ‘P_0’*”; in Option 2, the functional unit is defined as: “*the management of 1 tonne of the CW fraction ‘i’*”.

Starting from equations 1-4, the possible simplifications are: (1) only one CW fraction “i” appears; (2) the value of the quantity ´q_i´ generated is 1 tonne; and (3) the value of the quantity ´q'_i is 0 tonnes, since no waste is generated in prevention scenario *‘P_0’*. The resulting simplified equations 5-8 are shown below.

5. $(\chi_1)_i^j = \alpha_i^j + \omega_i^j$
6. $(\chi_{P1})_i^j = 0$
7. $(\chi_2)_i^j = \omega_i^j$
8. $(\chi_{P2})_i^j = -\alpha_i^j$

- $(\chi_1)_i^j$ is the impact 'j' of 1 tonne of the CW fraction 'i' generated in non-prevention scenarios 'NP^n' in Option 1.
- $(\chi_{P1})_i^j$ is the impact 'j' of 1 tonne of the CW fraction 'i' prevented in prevention scenario 'P$_0$' in Option 1.
- $(\chi_2)_i^j$ is the impact 'j' of 1 tonne of the CW fraction 'i' generated in non-prevention scenarios 'NP^n' in Option 2.
- $(\chi_{P2})_i^j$ is the impact 'j' of 1 tonne of the CW fraction 'i' prevented in prevention scenario 'P$_0$' in Option 2.
- ω_i^j is the impact 'j' associated to the downstream processes of 1 tonne of the CW fraction 'i' generated in non-prevention scenarios 'NP^n'.
- α_i^j is the impact 'j' associated to the upstream processes of 1 tonne of the CW fraction 'i' generated in non-prevention scenarios 'NP^n'.

4. Case study

A case study that assesses the potential impact of a representative environmental category is included to illustrate the approach of the proposed models.

4.1 Description

The general and simplified models were applied to the CW generated during the construction of a residential building, located in Seville (Spain) within a Research Project (Andalusian Government 2016). The main characteristics of the building are shown in Table 2.

Table 2
Characteristics of the building selected

Location	Seville (Spain)
Developer	EMVISESA
Construction company	VIAS
Typology	New multi-family residential (109 dwellings)
Built area	13910 m^2
Number of storeys	5-8
Structure	Cast in situ columns and beams
Floors	Cast in situ waffle slab
Roofing	Cast in situ flat roof
Masonry	Brick walls
Interior Wall finishes	Gypsum plaster and painting
Floor finishes	Ceramic and terrazzo tiled finishes

The case study was chosen as it is considered to be a representative situation of the current prevailing construction programmes in the Andalusian area, as shown in Table 3. Therefore, the case study focused on new residential buildings (Spanish Government 2015). In Spain, there is also a higher incidence of multi-family buildings with a greater number of floors than four-storey residential buildings (Spanish Government 2015), an aspect that was also taken into account in the case study.

Table 3
Statistical characteristics in Spanish Buildings. Types of buildings in Andalusia, Spain (Spanish Government 2015)

Typological Characteristics	**Number of buildings/year (%)**	
	Spain	**Andalusia**
Buildings by type of construction		
new residential buildings	37	38
new non-residential buildings	29	28
renovated buildings	8	10
demolished buildings	26	23
Type of housing		
single-family buildings	32	36
multi-family buildings	68	64
Number of storeys		
0-1 floors	8	8
2 floors	26	36
3 floors	15	18
≥3 floors	51	38
Structure		
in-situ concreting	72	91
steel	6	2
brick walls	15	5
mixed and other	7	2
Floors		
in-situ concreting	35	50
others	65	50
Roofing		
flat roof	50	65
pitched roof	50	35

4.2 Application of the general model

The general model was applied in order to show the usefulness and validity of its methodological approach and to evaluate the environmental impact of CW management in non-prevention and prevention scenarios.

4.2.1 Evaluation of CW non-prevention and prevention scenarios

Three non-prevention scenarios and one prevention scenario were considered as shown in Table 4. Within the non-prevention scenarios, NP^1 comprises the most unfavourable option of waste management hierarchy as it considers the disposal of all fractions; NP^2 is more favourable than NP^1 since it takes into account the recycling of all the recyclable CW fractions (specifically concrete, ceramic, iron and wood), and NP^3 is not as favourable as NP^2 but it is more viable since it takes into account the existence of recycling plants (specifically concrete and ceramic) for each waste fraction.

Table 4
Characteristics of non-prevention (NP^n) and prevention (P_i) CW management scenarios

Scenario type	Implementation of prevention activities	Selective separation	Waste treatment
NP^1 scenario	No	On the building site	Disposal of all the fractions
NP^2 scenario	No	On the building site	Recycling of recyclable fractions / Disposal of the rest
NP^3 scenario	No	In the waste sorting plant	Disposal or recycling according fraction and data sorting plant
P_1 scenario	Yes	On the building site	Recycling of recyclable fractions / Disposal of the rest

The CW inventory for both non-prevention and prevention scenarios was obtained by using the quantification tool developed by the Andalusian Government (2016). In prevention scenario ‘P_1’, both optimization and replacement measures shown in Table 5 were taken into account in order to design building systems that generate less waste.

Table 5
CW prevention activities applied to the building systems of the selected building in prevention scenario P_1

Building System	Optimization measures	Replacement measures
Foundation	Dimensional coordination between foundation and structure elements. Modulated foundation elements. Foundation elements designed with optimization criteria. Equalization between excavated soil and backfill material.	Use of prefabricated foundation elements instead of elements cast in situ.
Sanitary facility	Sanitary facility elements designed with optimization criteria. Reuse of soil from trenching in its filling.	Use of prefabricated catch-basins instead of brick wall catch-basins.
Structure	Dimensional coordination between structure and foundation elements. Dimensional coordination between structure and masonry elements. Modulated structure elements. Structure elements designed with optimization criteria.	Use of pre-cast concrete hollow core slabs instead of floors cast in situ. Use of pre-cast concrete columns and beams instead of casts executed on-site. Use of dry joints instead of wet joints.
Masonry	Dimensional coordination between façade and structure elements. Dimensional coordination between partition and structure elements. Modulated masonry elements. Masonry elements designed with optimization criteria. Modular window openings. Avoidance of the use of cut bricks (e.g. use of special pieces).	Pre-cast concrete panels in façades instead of brick walls. Plasterboard panels in partitions instead of brick walls. Panels supplied with thermal and acoustic insulation. Uncoated façades and partitions.
Roofing	Roofing slopes designed with optimization criteria. Dimensional coordination between brick wall slopes and brick boards.	Non-adhered tiles. Tiles supplied with thermal and acoustic insulation.
Facilities	Tracing facilities outside the walls, without wall slots.	Prefabricated ventilation ducts instead of brick ducts.

Finishes	Coordination between tiles and coated surfaces. Flooring and ceilings designed without interruptions.	Use of technical floors instead of adhered tile finishes. Use of cladding stone and mechanical anchorage in walls instead of adhered tile finishes. Uncoated façades instead of on-site mortar coating. Uncoated partitions instead of gypsum plaster.

The tool is based on a CW quantification model (Llatas 2011) and a CW prevention model (Llatas and Osmani 2016). This tool, in addition to calculating the CW generated from the project, allowed the application of prevention measures and the estimation of the CW reduction achieved. Both optimization and replacement measures were applied to the building systems. Table 5 covers the most affected building systems as well as the main measures taken into account. It was assumed that the measures implemented should not affect the aesthetic design of the building or the terrain. Examples of optimization measures were the use of optimized structural elements and foundations (minimum volumes excavated, no oversized structures) and dimensional coordination between the building elements (walls, floors, tiles). With regard to replacement measures, prefabricated elements were used instead of elements performed in situ (e.g. prefabricated manholes versus brick masonry manholes) and the use of dry joints instead of wet joints (e.g. unbounded tiles versus mortar-adhering tiles). Other strategies applied included the use of building materials provided with optimized packaging or even without any packaging whatsoever, a suitable collection and supply of materials, the use of resistant building materials and special pieces, and the use of recoverable and durable auxiliary materials. With all these measures, the amount of the CW generated in prevention scenario ‘P_1’ was reduced by up to 60% and its composition differed with respect to non-prevention scenarios ‘NP^{1-3}, as shown in Table 6.

Table 6

Composition and amount (tonnes) of the CW generated in the selected building in non-prevention (NP^n) and prevention (P_i) scenarios

CW fraction	Non-prevention scenarios* NP^1, NP^2, NP^3	Prevention scenario* P_1
Concrete	404.00	160.00
Ceramic, bricks, tiles	197.00	78.10
Mix concrete and ceramic	105.00	41.70
Wood, timber formworks	4.94	1.96
Plastic, insulations	0.30	0.01
Copper, bronze, brass	0.42	0.16
Aluminium	0.27	0.11
Iron and steel	2.68	1.06
Gypsum-based	9.22	3.65

Mixed waste	42.20	16.70
Paper and cardboard packaging	5.69	2.25
Plastic packaging	6.85	2.72
Mixed packaging	5.01	1.98
Total	**784.00**	**310.00**

*CW management scenarios described in Table 4

4.2.2 Functional unit and system boundaries

The functional unit and system boundaries were defined for each methodological option. In Option 1, the functional unit was *"the management of the actual amount of CW generated in each scenario equal to 784 tonnes in non-prevention scenarios (NP^1, NP^2, NP^3) and 310 tonnes in a prevention scenario (P_1)"*, following the composition given in Table 6. In all scenarios, the system boundaries included the downstream and upstream processes for each CW fraction generated as shown in Figure 3. In Option 2, the functional unit was "*the management of 784 tonnes of CW"* following the composition of non-prevention scenarios presented in Table 6. The system boundaries included the downstream and upstream processes for each CW fraction generated. However, due to the application of the 'zero burden assumption', the upstream processes were excluded from the system boundaries of non-prevention scenarios, and appear as prevented loads in the prevention scenario as shown in Figure 3.

4.2.3. Quantification of environmental impacts: an example

The evaluation was carried out following the ISO 14040 and 14044 standards. The inventory data of the processes, according to the different stages included in the system boundaries, were mainly obtained from the Ecoinvent database (SCLCI 2008). Certain issues related to these processes include:

- In the construction stage, energy consumption due to the building construction was estimated in accordance with Kellenberger et al. (2007).
- In the end-of-life stage, the following processes were considered: on-site storage, transport, sorting (in NP^3 scenario), treatment, and disposal.
- Transport was modelled considering the type of lorry, the load and the distance covered, as well as the routes along which the lorry was unloaded, with lower fuel consumptions (JRC-IES 2011).
- In NP^2 and NP^3 scenarios, the primary products that were not consumed thanks to recycling were taken into account.

- Environmental burdens due to capital goods, such as infrastructure, machinery, and lorries, were not taken into account.

The software used for life-cycle impact assessment was SimaPro 7.1 and the environmental assessment method was CML 2001 (Guinée et al. 2001), with the climate change selected as a priority impact category (GWP – Global Warming Potential, in kilogrammes of CO_2 equivalence). The impact for this environmental category was estimated by applying equations 1-4 and is shown in Figure 4. The calculation of other categories of environmental impact would follow the same modus operandi.

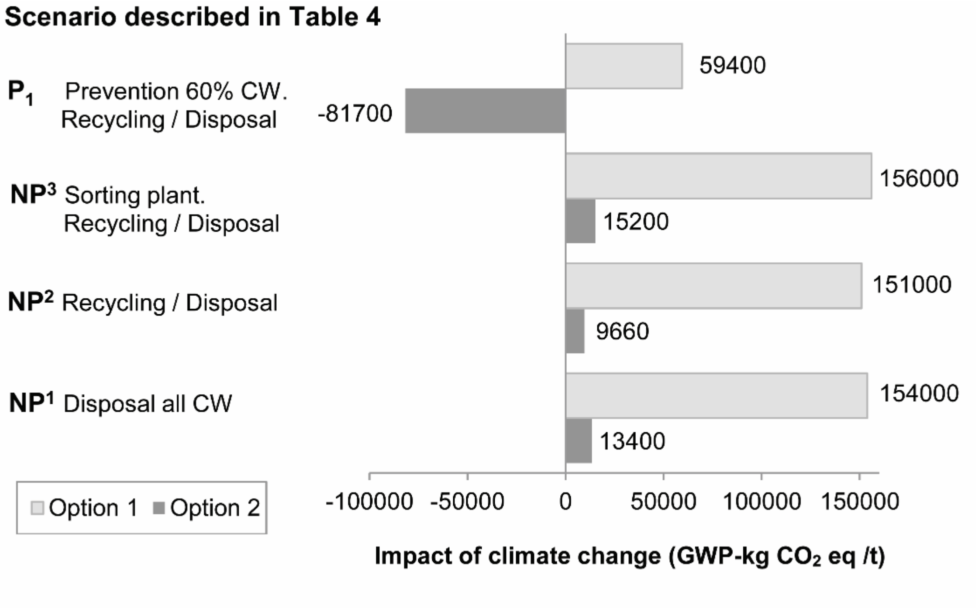


Fig. 4. Impact of climate change (GWP-kg CO2 eq/ t) in non-prevention (NP^n) and prevention (P_i) scenarios obtained by general model methodological options

4.3 Application of the simplified model

The two options of the simplified model were applied to the management of 1 tonne of concrete waste in order to illustrate its approach and to evaluate the environmental impact of the management of the concrete fraction, in non-prevention and prevention scenarios.

4.3.1 CW non-prevention and prevention scenarios evaluated

Table 7 describes three non-prevention scenarios (NP^1, NP^2, NP^3) and one prevention scenario (P_0) taken into account in the management of the concrete fraction. In the NP^2 and NP^3 scenarios, the waste treatment considered was that of recycling. However, the NP^2 scenario considered a selective separation of the concrete fraction on the building site, while in the NP^3 scenario, concrete waste was separated in the sorting plant. In prevention scenario 'P_0', only optimization measures were taken into account, thereby preventing the generation of any waste.

Table 7
Characteristics of non-prevention (NP^n) and prevention (P_0) scenarios evaluated in the management of 1 tonne of concrete waste

Scenario type	Concrete waste generated	Selective separation	Concrete waste treatment
NP^1 scenario	Yes (1 tonne)	On the building site	Disposal
NP^2 scenario	Yes (1 tonne)	On the building site	Recycling
NP^3 scenario	Yes (1 tonne)	In the waste sorting plant	Recycling
P_0 scenario	No (0 tonnes)	Not applicable	Not applicable

4.3.2 Functional unit and system boundaries

The functional unit and system boundaries were defined for each option. In Option 1, the functional unit was the management of the actual amount of CW generated in each scenario: '1 tonne of concrete waste' in non-prevention scenarios and '0 tonnes' in the prevention scenario. In all 4 scenarios, the system boundaries included the downstream and upstream processes for the concrete as shown in Figure 3. In Option 2, the functional unit was 'the management of 1 tonne of the concrete fraction'. The system boundaries included the downstream and upstream processes. However, due to the application of the 'zero burden assumption', the upstream processes were excluded from the system boundaries of the non-prevention scenarios '$NP^{1\text{-}3}$', and appear as prevented loads in the prevention scenario 'P_0', as shown in Figure 3.

4.3.3. Quantification of environmental impacts: an example.

The inventory analysis and the impact assessment were both carried out in the same way as in the general model: the inventory data of the processes involved in the study was obtained from the Ecoinvent database (SCLCI 2008), the software used for life-cycle impact assessment was SimaPro 7.1, and the environmental assessment method was CML 2001 (Guinée et al. 2001), with the climate change selected as a priority impact category (GWP – Global Warming Potential, in kilogrammes of CO_2 equivalence). This impact was obtained by applying equations 5-8 and is shown in Figure 5. The calculation of other environmental impact categories in other prevented CW fractions would follow the same modus operandi.

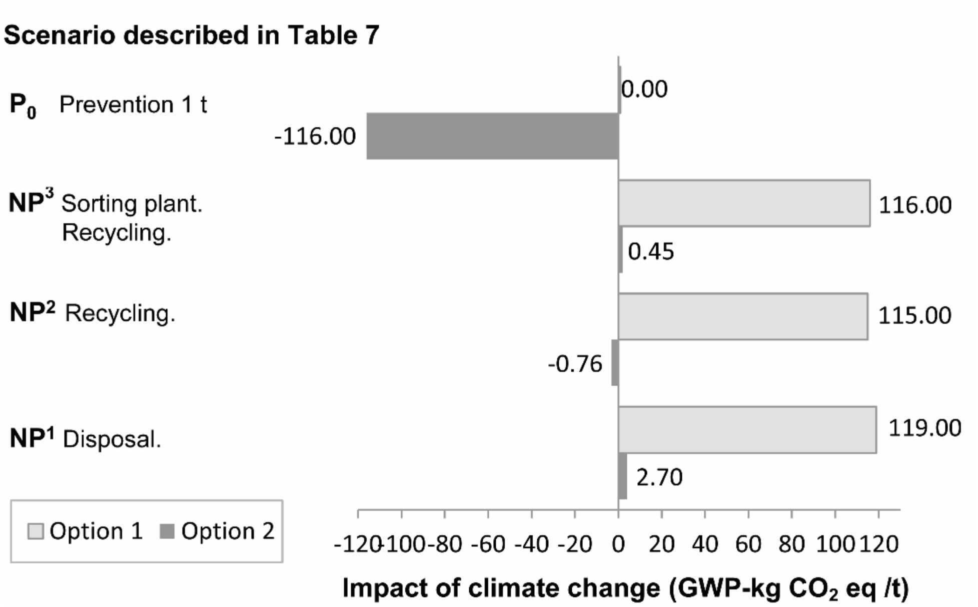


Fig. 5. Impact of climate change (GWP-kg CO2 eq/ t) due to the management of 1 tonne of concrete waste in non-prevention (NP^n) and prevention (P_0) scenarios obtained by simplified model methodological options

5. Discussion

The redefinition of the functional unit and the system boundaries allowed the assessment of prevention scenarios in the traditional LCA of CW management. In the case study, for example, prevention was the most environmentally friendly scenario, since in addition to reducing the amount of CW generated, CO_2 emissions were also reduced compared to non-prevention scenarios. In the general model, a 60% CW reduction in non-prevention scenarios led to a reduction of up to 62% of CO_2 emissions. One main reason for this reduction is that the downstream loads were much higher than the upstream loads, and hence the prevention of CW generation influences the overall result significantly. On the other hand, non-prevention scenarios were the least environmentally friendly scenarios, and obtained similar impacts. This was due to the similar magnitude in the impacts of the downstream processes of recycling and disposal scenarios. Moreover, recycling was not the most beneficial scenario with respect to disposal in all cases, due to the high energy consumption resulting from the selective waste separation in the sorting plant as well as from the recycling process itself.

In both models (general and simplified), the results obtained by Option 1 are the real impacts of the management of CW that is generated and prevented on construction sites, and the results obtained by Option 2 are those that result from applying the 'zero burden assumption' in the same way as by the traditional

LCA of CW management. The negative results are interpreted as environmental benefits and positive results as adverse impacts. In Option 1, each scenario includes both upstream and downstream processes, however, in Option 2, only the upstream processes are included in the prevention scenario, since prevention is considered as a management option.

As demonstrated by the case study, the system boundaries are relevant to the interpretation of the results of each methodological option. In the case of the general model, the prevention scenario is positive in Option 1 and negative in Option 2. However, the real impact, which is an adverse impact, is that obtained using Option 1. Therefore, the interpretation of the results of Option 2 as an environmental benefit must be performed within the system boundaries considered. In the case study of the simplified model, it is observed that, in Option 1, all scenarios are positive or zero, while in Option 2, both recycling ‘NP^2’ and prevention ‘P_0’ scenarios are negative. In this case, it could even lead to the paradoxical conclusion that generating and recycling waste is more beneficial environmentally than prevention, as reported by Nessi et al. (2013).

Another significant issue is that, in absolute terms, the difference in impacts between scenarios coincides using Options 1 and 2, both in the general and simplified models. This difference is equal to the upstream burdens of the CW generated, thereby obtaining identical conclusions regarding the suitability of one scenario over another with either of the methodological options. However, in relative terms, the differences between scenarios differ, since the results of each scenario vary depending on the applied option, and it is necessary to interpret the results according to the characteristics of each methodological option. This can be verified in the case study of the simplified model for the fraction of concrete according to the GWP impact category. The absolute difference between the ‘NP^1’ and ‘NP^2’ scenarios is 3.46 kg $CO_{2\ eq}$; and between the ‘NP^3’ and ‘NP^1’ scenarios this is 2.25 kg $CO_{2\ eq}$. However, in relative terms, using Option 1, the ‘NP^2’ and ‘NP^3’ scenarios are 3% and 2% more environmentally friendly than the ‘NP^1’ scenario; and with Option 2, these percentages amount to 128% and 83% respectively.

With regard to the comparison with other studies, in the general model only those results obtained for non-prevention scenarios with Option 2 could be referred to as results of the traditional LCA of CW management. However, the functional unit of Option 2 does not allow comparison with other case studies that analyse a different CW quantity and composition. In the case of the simplified model, Option 1 allows the comparison of 1 tonne of different CW fractions with each other; but Option 2 can be misleading because when the ‘zero burden assumption’ is applied, it penalizes or benefits each CW fraction depending on the magnitude of the upstream loads.

Concerning the usefulness of each methodological option, Option 1 is more suitable for those LCAs aimed at helping in the decision-making concerning preventive measures during the design phase, since it allows monitoring of the actual impact that CW causes in construction work, in a building element or a separate CW fraction. However, Option 2 facilitates the interpretation of loads saved by CW not generated in prevention scenarios. Therefore, Option 2 may be more useful in LCAs whose objective is the decision on the choice of optimal CW management from options that may include prevention scenarios.

Finally, the use of LCA to evaluate CW management involves collecting specific data in each construction project analysed. This means the investment of a considerable amount of time, which is increased if scenarios include prevention, since, in addition to the data of the downstream processes, it is also necessary to collect the data of the upstream processes. Moreover, the case study is focused on a prevention scenario, a representative impact category (climate change), and a fraction of waste (concrete). Future applications of the models in buildings could assess other prevention scenarios (e.g. the use of volumetric prefabrication), other environmental impact categories (energy, acidification, land use) and other prevented CW fractions (ceramic, plastic, metal) in various types of buildings (commercial, industrial, office).

6. Conclusions

The environmental and energy impact of CW management scenarios that include prevention activities can be evaluated from the perspective of the life-cycle through the approaches of the two models presented in this article. In the literature reviewed, there is a clear lack of LCA approaches that assess the CW management with the inclusion of prevention scenarios that reduce the amount of CW generated on-site. The redefinition of the functional unit and system boundaries allows the inclusion of prevention scenarios along with recovery and disposal scenarios considered in the traditional LCA of CW management. In addition, most CW prevention studies in the reviewed literature are focused on the effects of prevention measures in the reduction of the amount of CW. The methodological approaches in this research study enable further in-depth knowledge to be explored on the effects of prevention measures in reducing the CW environmental impact. In the case study, for example, prevention activities in the building not only achieve a reduction of 60% by weight of CW generated on the building site, but it 1also reduces by 61%, the CO_2 emissions that would be produced in a non-prevention scenario.

This study has a double scope. On the one hand, regarding the Member States of the European Union, it could support the preparation of national waste prevention programs by using LCA tools. On the other hand, designers could be assisted through the development of guidelines supported by the methodologies presented in this study. Option 1 of the general model could help decision-making on preventive measures during the design phase. Option 2 of the general model could serve to quantify CW impacts once generated. Option 1 of the simplified model could serve to make decisions about the materials to be included in building systems with waste prevention criteria. Option 2 of the simplified model would help towards determining the best management option for each CW fraction once generated, thereby allowing the quantification of the reduction of impacts that could have been achieved if they had been prevented.

According to the EU Waste Framework Directive (European Commission 2008), the aim of prevention objectives and measures is to break the link between economic growth and the environmental impacts associated with the generation of waste. Therefore, this study would allow the inclusion within these guidelines not only of the amount of CW and economic indicators but also of indicators of other environmental impacts (climate change, resource consumption) relating to prevention measures considered in waste management policies and strategies.

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