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Title: Is selective demolition always a sustainable choice?

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Keywords: construction and demolition waste; building; life cycle assessment; environmental assessment; demolition

Corresponding Author: Dr. lucia rigamonti, Ph.D.

Corresponding Author's Institution: Politecnico of Milan

First Author: Sara Pantini

Order of Authors: Sara Pantini; lucia rigamonti, Ph.D.

Abstract: Selective demolition is usually perceived as essential for a sustainable built environment since it aims to maximise the valorisation of constituent building materials and components giving them a new life. The successful diversion of construction materials from landfill and the extent of recovery of construction and demolition wastes as secondary raw materials depend on how the demolition work is executed, as well as on the logistic and economic aspects of the geographic context. The main goal of this study is to critically explore the sustainability of selective demolition practices versus traditional ones by addressing the environmental issues through the Life Cycle Assessment methodology. The key parameters that determine the environmental profile of a selective demolition project and their effects on the overall environmental balance were identified. Primary site-specific data supplied by the demolition companies involved in the demolition of a residential building located in Milan (Northern Italy) were used in the analysis. The results indicate that the environmental sustainability depends a lot on the characteristics of the building to be demolished as well as on the local markets for recycled materials. Moreover, the benefits from substituting primary raw materials can be overset by the increased impacts due to additional energy requirements of the selective demolition in comparison to the traditional one. Consequently, the environmental sustainability of selective demolition should be addressed on a case by case basis.

***Detailed Response to Reviewers**

Editor' Comment	Author' Response	Revised Text
The paper provides original results and conclusions on a selective demolition case study. Main issues to be tackled: 1) Significant revisions are needed to improve the language: the paper needs professional proofreading in order to fulfill the language standards of a scientific journal. also, use consistent wording throughout the text. Many times different wording is used for the same element, confusing the reader.	Thank you for your comment. The paper has been extensively revised by paying a particular attention to the wording.	See the revised paper
2) Readability and clarity of Figure 1 and 2 need to be improved.	The caption of Figures 1 and 2 has been improved and an explanation has been added in the text. Moreover, we realized that there was a mistake in Figure 1 (first line of diagrams) that has been corrected.	See new Figure 1, see the revised captions of Figures 1 and 2 and lines 318-323
3) The study objectives and some analysed options need to be clarified and updated.	The paper has been extensively revised according to the detailed comments of the reviewers. We hope that now objectives and methodology used in the study are clearer.	See the revised paper.

Reviewer #1' Comment	Author' Response	Revised Text
Given the validity of this study, some small improvements are suggested, in order to increase the effectiveness and understanding of the work. 1) A first suggestion is to provide (in the methodology section) a brief introduction of the LCA method in its fundamental features, without, however, going too far. This could facilitate the understanding of the experiment for those readers who are not very familiar with this technique.	As suggested, a brief introduction of the LCA method has been included in the methodology section.	See lines 81-90
2) Another suggestion concerns the data on the amount of waste materials produced (from line 108). When it is not possible to obtain directly these data, there are other techniques that could be worth mentioning, apart from direct measurements. Inserting this information could allow to improve the completeness of this section also from a literary point of view. Indeed, apart from the waste materials produced during the soft stripping, provided by the company, it could be useful to be more precise when describing the methodology used for the quantification of the waste stream produced during the structural deconstruction.	The amount of CDW streams has been computed by summing the wastes produced from the stripping phase (directly available since this stage was already concluded) and those arising from the deconstruction and demolition phases. The latter data were estimated from the available measured data, which are indicated as "partial" since they only refer to the demolition of 1 floor out of the four. The total amount of CDW generated during the demolition phase was obtained just multiplying by 4 the field data (all building floors are almost similar): this aspect has been better specified in the revised version. As stated by the reviewer, other techniques for C&D waste quantification exist that can be used alternatively to direct measurements. These methods require for a deep knowledge of the building (construction techniques, building elements, building history etc.) and may introduce further uncertainties, so direct measurements of waste materials are preferred if available. However, as suggested by the reviewer, we have mentioned in the revised paper some waste quantification methods for sake of completeness.	See lines 137-138 and lines 138-143

3) One or more photos of the building under analysis and/or an overview of the territory in terms of location of the building and eventually of some of the most significant waste treatment plants could enrich the description of the case study.	Unfortunately, we do not have photo of the building but only the planimetry of building floors. The building is located in Milan (see line 80) and all treatment plants receiving the waste materials are reported in Table 1 with the indication of the transport distance from the working site. Specific information about the CDW treatment process have been added; further information can be found in Borghi et al., 2018.	See lines 219-222
4) I suggest to make Table 1 a little more homogeneous: if EWC 170107 has an output in the form of recycled aggregates, also for the other fractions the type of output that emerges from the recycling process could be indicated, if this information is known.	Following the reviewer's suggestion we have updated Table 1 highlighting the type of output from each recycling process related to mineral CDW, glass, steel, wood and aluminium.	See the revised Table 1
5) When speaking about high quality and low quality recycled aggregates, it could be important to specify better the characteristics of recycled aggregates (high, medium and low quality) and the relative possible uses (Circular 5205/2005). Furthermore, if this information is known, I suggest to specify the typologies of the recycling plant for the production of recycled aggregates (stationary, semi-mobile or mobile).	The characteristics and possible uses of RAs according to the Italian Ministerial Communication 5205/2005 have been added in the revised paper. Our previous research presented in Borghi et al., 2018 have pointed out that the type and quality of CDW entering the recycling plant is by far much more important than the type of applied recycling technology. Stationary CDW plants are less widespread (13.9% in Lombardy region) compared to semi-mobile plants, while mobile plants are very rare due to difficulties in the permitting process. We have added in the revised version a sentence about the typologies of recycling plants in Lombardy. From the technological point of view, stationary plants implements more efficient treatments and devices but the quality of RAs is still of medium-low quality. If the initial CDW is strongly heterogeneous, the final RAs still cannot comply with the	About the quality of recycled aggregates, see lines 238-249 and lines 252-267. About the typologies of recycling plants, see lines 219-222.

	more stringent quality criteria set for high grade applications (aggregate for base layer – attachment C3 and aggregate for concrete production – attachment C6) due to technological limitations (e.g. it is very hard to separate concrete from bricks; in turn, the content of bricks and ceramics reduces the RAs resistance to fragmentation preventing the use of RAs in "structural applications").	
6) Line 215: substitute "associate" with "associated".	Done	Associated
7) When discussing about results, it could be significant to compare them with results from similar studies, in order to observe the variability of the conclusions drawn depending also on other analysis contexts.	Comparing the results of different LCAs can be difficult due to the different functional unit applied, the different system boundaries considered, the different location of the study or building type, the different LCA methodology implemented and so on. These differences can be responsible for significant variation in terms of sustainability. However, we have added in the results sections a comparison with previous studies.	See lines 348-359 and lines 366-375

Reviewer #2' Comment	Author' Response	Revised Text
The paper is an important contribution to the sector. This is a relevant issue, with an appropriate approach. The paper structure and the basic literature are correct, and I believe it will be a reference work.	Thanks for your comment	-

Reviewer #3' Comment	Author' Response	Revised Text
I would like to thank you very much for the paper, which in my opinion provides original results on a selective demolition case study. I believe that you have presented useful discussion points and conclusions. I have some general remarks and more specific comments, which I kindly ask you to consider and address in order to improve the consistency and the clarity of the paper. I would also suggest sending the paper to professional proofreading.	Thanks for your comment. The paper has been extensively revised as you can see looking at the new version.	-
A. General comments I would suggest better clarifying in the Introduction which are the objectives of the study and which operations are considered under selective demolition. In detail, you refer to deconstruction activities (lines 14-15, 18, 33, 42, 102-104, etc.), dismantling activities (line 30), dismantling and sorting activities (line 55), disassembling activities (line 44) and soft-stripping (102). It is not clear if selective demolition encompasses all these activities. The EU Construction & Demolition Waste Management Protocol (2016) could be a good reference guidance for the wording and definitions to use.	As defined in the EU CDW management Protocol 2016, selective demolition involves a sequence of activities to allow the separation and sorting of building materials: this has been clarified in the revised paper. The text has been checked for the wording used. Regarding the demolition activities, a selective demolition project may include the following activities: site preparation and decommissioning (e.g. removal of all engineering devices and welfare facilities, finishing elements, furniture, asbestos, chemicals and so on); soft-stripping (e.g. the removal of non-structural elements); disassembly of building components and sorting (e.g. partitions, roof); demolition of structural elements. The extent of implementation of each activity depends on several factors such as the building characteristics, the project technical constrains (space, time, noise), the competence and experience of contractors and site workers, the marketability of re-used, recovered or recycled materials, costs and so on. So	- See lines 35-38 - "deconstruction" was replaced with "selective demolition" throughout the revised paper - See lines 125-132

	there is not only a way to conduct selective demolition. In our specific case study, the performed demolition activities are specified at lines 125-132 of the revised paper.	
I would also suggest specifying that only traditional mechanical techniques have been considered and other traditional methods may apply (such as explosives).	This has been added in the revised paper.	See lines 168-171
You often refer to recovered materials. I would suggest specifying "recovered materials" or "recycled materials", considering that recycled aggregates are the main materials produced through CDW recycling (see line 21). Sometimes a less proper wording is used and should be revised (for example "exploitation of waste" at line 35). Please, check the consistency of the wording and refer to CDW recycling where appropriate (check, for example, lines 243, 257, 308).	The text was checked to improve the wording.	"Recycled" is now used instead of "recovered" for all materials obtained from recycling processes. "Exploitation of waste" was changed in "Valorisation of waste" or "Recovery of waste".
I would also suggest referring to primary or secondary raw materials, rather than to primary/secondary materials (lines 39, 166), virgin/ primary or secondary resources (lines 36, 49, 180), primary or secondary products (lines 78, 215). Please make also specific reference to natural aggregates (NA) and recycled aggregates (RA) when you are dealing with the recycling of the mineral part of CDW (see lines 188, 192).	The paper has been revised according to this comment.	Throughout the revised text: "primary raw materials" or "secondary raw materials" and "NA" or "RA"
Please better define and describe the market factor (lines 89, 195, 273). Does your analysis only focus on the replacement of natural aggregates by recycled aggregates, or if a larger number of secondary raw materials is considered (for example recycled metals and related avoided impacts)? Please clarify also the RA market variation used in Figure 1. How is the quality of RA taken into consideration?	The market factor cited at lines 89, 195 and 273 refers specifically to the average market demand of RAs in the Lombardy region. As now stated at lines 111-112, it was estimated as the ratio between the amount of RAs sold and the total RAs produced from CDW recycling plants in the Lombardy Region. For more information please refer to	See lines 111-112 for the market factor See lines 318-323 for an explanation of Figure 1 See lines 252-267 for the quality of RAs

	Borghi et al., 2018. This LCA also includes the avoided impacts due to placement on the markets of other secondary raw materials coming from the recycling of steel, glass, wood and aluminium. The market factor for all these recycled materials has considered equal to 1 due to their high economic value (aluminium and steel) and the existing of well-established value chains in the region (glass and wood) (see line 261). For these materials, the replacement factor (i.e. product of the market factor by the quality factor) was already reported in Table 2 and only depends on technical properties of secondary materials compared to primary ones. The variation of RAs market factor in Figure 1 is expressed as percentage from the value assumed in the baseline (0.67): -100% variation corresponds to a null market factor (RAs are totally unsold) while +49% variation correspond to a market factor of 1 (all RAs are sold). An explanation of Figure 1 has been added. The quality of RAs has been taken into consideration as now better described in lines 256-266.	
This paper deals with CDW (as specified in Table 1). However, you often refer generically to waste (see for example lines 108, 143, 152, 166, 227, 266, 280, 299, 300) and this decreases the article clarity. Please, check the consistency of the wording used.	The text has been checked and the word “waste” was replaced with “CDW”.	CDW
Please, also clarify if and how the re-use option, both on site and off site, has been considered (see line 91-92).	We have specified that the re-use option was applied neither on site nor off site (lines 149-150)	the re-use of sorted components both on site and off site did not take place at all
I would suggest improving the	An explanation of Figures 1	See lines 31-323 for

readability and clarity of Figure 1 and 2. Please clarify how the RA market variation and the change in iron and steel amount are evaluated. Check the x-axis scale used. Please also better clarify which is the considered baseline scenario.	and 2 has been added in the text and the caption of Figures 1 and 2 has been improved. The variations of each system's parameter displayed on the x-axis were arbitrary set by increasing or decreasing the initial value assigned in the baseline scenario. There was a mistake in the trends related to the global warming and CED with the variation in the market factor; Figure 1 has now been corrected. We also have clarified the main assumption of the baseline scenario and the other analysed scenario.	explanation of Figures 1 and 2. See lines 257-267 for an explanation of the scenarios. See new Figure 1 and captions of Figures 1 and 2
In the traditional demolition scenario, you assume that reinforcement bars are not contained in the mixed CDW sent to the recycling facility. It is specified that they are liberated from the crushed concrete by means of excavator grapples (lines 137-139). Please clarify if this operation is done at the demolition site or at the recycling facility. Anyhow, reinforcement bars are also liberated by primary/secondary crushing and magnetic separation at the recycling plant. In this regard, please check EC, BIO-IS 2011 https://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf, the EU Construction & Demolition Waste Management Protocol (2016) (see figure at p. 24) and Pacheco-Torgal, Tam, Labrincha, Ding and de Brito, Handbook of recycled concrete and demolition waste (2013), Woodhead Publishing Limited). I would suggest updating your analysis accordingly.	This operation is done both at the demolition site and at the recycling activities. We have specified this in the revised text.	The remaining bars (the separation at the demolition site does not have an efficiency of 100%) together with all other building materials (wood, glass, plastics, exc....) are supposed to end up
The main revisions relate to the language used. I have pointed out some words/phrases to be specifically checked and revised (highlighted in yellow in the attached pdf). However,	All the highlighted words/phrases in the pdf have been checked and revised.	See the revised paper and the response to comments below about specific words / sentences.

I would suggest sending the paper to professional proofreading in order to reach the language standards of this journal. B. Specific comments and suggestions		
Line 16-19) Please consider splitting the phrase.	The suggestion has been taken into consideration in the preparation of the revised paper.	The key parameters that determine the environmental profile of a selective demolition project and their effects on the overall environmental balance were identified. Primary site-specific data supplied by the demolition companies involved in the demolition of a residential building located in Milan (Northern Italy) were used in the analysis.
Line 20) I would suggest rephrasing as "strictly depends".	The suggestion has been taken into consideration in the preparation of the revised paper.	depends a lot
Line 22) As for the analysed system, I would suggest refer to the analysed case study.	This part was deleted.	-
Line 22-24) I would suggest rephrasing and clarifying these remarks.	The suggestion has been taken into consideration in the preparation of the revised paper.	See lines 21-26
Line 33) I would suggest rephrasing as "point of view".	The suggestion has been taken into consideration in the preparation of the revised paper.	point of view
Line35) I would suggest rephrasing as "and consequent land use preservation".	The suggestion has been taken into consideration in the preparation of the revised paper.	and consequent land use preservation
Line 37) I would suggest rephrasing as "both at local and global scale".	The suggestion has been taken into consideration in the preparation of the revised paper.	both at local and global scale
Line 38) point iv) perhaps a verb is missed. Please rephrase.	The suggestion has been taken into consideration in the preparation of the revised	reduction in overall demolition costs through landfill

	paper.	charge savings and revenues from the sale of secondary raw materials
Line 44-47) Please, clarify the wording and consider splitting this phrase.	The suggestion has been taken into consideration in the preparation of the revised paper.	See lines 51-55
Line 49) Please clarify which is the relationship between material separation rate and the possibility of re-using building components on site.	We are not aware of a specific relationship between the material separation rate and the possibility of re-using building components on site. We are just saying that the extent of materials separation may be influenced by the possibility of re-using them on site.	-
Line 51) I would suggest rephrasing as "is composed of small and medium enterprises".	The suggestion has been taken into consideration in the preparation of the revised paper.	is composed of small and medium enterprises
Line 51-53) Please, clarify the wording and consider splitting this phrase.	The suggestion has been taken into consideration in the preparation of the revised paper.	The construction industry is mostly composed of small and medium enterprises, operating under a tight profit margin. Consequently, they do not take efforts in implementing reuse and recycle programs without an immediate economic profit.
Line 70-71) Please, consider splitting the phrase: A real case study, i.e….., has been considered.	The suggestion has been taken into consideration in the preparation of the revised paper.	This LCA study aims to understand how and to what extent the use of different demolition techniques can influence the performance of the system under study in terms of environmental and energetic loads. A real case study, i.e. the selective demolition of a residential building

		located in Milan (Northern Italy), has been considered.
Line 92) Please clarify if you mean "incineration of plastic waste". However, please explain why in Table 1, the incineration scenario has not considered, while it is reported as a result (lines 267-268).	Here we mean incineration of different streams instead of their disposal. In particular, as it can be seen in Figure 2, we have tested the cases of incineration of plastics and incineration of non-mineral mixed CDW. In Table 1 the incineration scenario is not reported because Table 1 refers to the baseline scenario and not to sensitivity and scenario analyses.	-
Line 95) I would suggest rephrasing as "selective demolition case study".	The suggestion has been taken into consideration in the preparation of the revised paper.	selective demolition case study
Line 99) I would suggest rephrasing as "hazardous components and materials".	The suggestion has been taken into consideration in the preparation of the revised paper.	hazardous components and materials
Line 100) I would suggest rephrasing as "technical building systems".	The suggestion has been taken into consideration in the preparation of the revised paper.	technical building systems
Line 103) Do you mean "structure deconstruction"? The deconstruction of structural elements is included in the subsequent step, as far as I understand.	We mean the deconstruction of structural elements. The subsequent step is the demolition (not the removal of some elements).	deconstruction of structural elements
Line 110-111) Please rephrase and clarify.	The suggestion has been taken into consideration in the preparation of the revised paper.	Specifically, the available measured data, which refer to the demolition of one floor, were multiplied by 4 to obtain the waste originated from steps (ii) and (iii).
Line 111-114) Please consider splitting the phrase.	The suggestion has been taken into consideration in the preparation of the revised paper.	The total CDW generation rates for each waste category are reported in Table 1, together with the final destination and the transport distance associated to each step of their

		own recycling/disposal route. In all cases, CDW transportation occurred with Euro 6 trucks.
Line 115-116) Please consider rephrasing.	The suggestion has been taken into consideration in the preparation of the revised paper.	On the contrary, the re-use of sorted components both on site and off site did not take place at all.
Line 117-122) Please consider splitting the phrase or including bullet points.	The suggestion has been taken into consideration in the preparation of the revised paper.	CDW landfilling only accounted for about 28.5 t/m^2. It comprises:
Table 1, second row: I would suggest rephrasing "Destination and relative transport" with "Treatment / disposal options, including transport distances". I would also include in the footnote that transportation was done by Euro 6 trucks.	We have made the rephrasing as suggested. We think it is not necessary to add a footnote about the transportation as this aspect is explained in the main text.	Treatment / disposal options, including transport distances
Line 142-143) Considering that the FU is 1 m2, why the consumption is not expressed in kWh/m2 and MJ/m2?	The consumption is already expressed in terms of the functional unit.	0.2 kWh/FU and 311 MJ of diesel/FU.
Line 147) I would suggest rephrasing as "Ministerial Communication". Please consider that this Communication deals not only road construction works (sub-grade, sub-base, base) but also environmental rehabilitation and backfilling.	The suggestion has been taken into consideration in the preparation of the revised paper. We have changed the point in the sentence where we introduced the reference.	The manual sorting is necessary to guarantee the compliance of RAs with the Italian quality requirements (Ministerial Communication n. 5205/2005 of the Italian Ministry of the Environment, Land and Sea) set for their use in road construction works
Line 148) Please, explain better what is a "common recycling process".	The sentence has been deleted.	-
Line 149) I would suggest rephrasing as "lightweight impurities".	The sentence has been deleted.	-
Line 154-157) Please, rephrase having in mind that the Italian communication refers to perishable materials (wood, paper, textiles fibers, etc.) and considers them as impurities. Please, better clarify which limits refer to road construction works or to environmental rehabilitation and	The suggestion has been taken into consideration in the preparation of the revised paper.	The content of the following materials appeared as critical: wood content of 0.187% (limit value set by Ministerial Communication n. 5205/2005, all

backfilling.		attachments: <0.1%); plastics content of 0.193% (limit value set by Ministerial Communication n. 5205/2005, all attachments: <0.1%); and gypsum content of 0.717%, that fails to meet even the least stringent limit (<0.6%) related to the uses in embankments and fillings (attachment C4 of the Ministerial Communication n. 5205/2005).
Line 158-164) Please clarify which assumptions have been made on transportation distances.	The assumptions have been added in the revised paper.	The more intense manual sorting step was then modelled prior to the CDW recycling treatment to remove: 6.05 kg/m^2 of gypsum wastes, disposed in landfill (distance: 59 km - average between the distances of the two landfills in Lombardy that receive gypsum waste from the recycling plant); 1.65 kg/m^2 of wood, sent to another landfill site (distance: 27.5 km; Borghi et al., 2018); 1.77 kg/m^2 of plastics that are landfilled due to their dirty nature (distance: 35 km – same distance as in the selective demolition scenario)
Furthermore, please explain in what	It’s the same	This step

the sorting step (line 157) differs from the pre-sorting step (line 160).		
Line 170) I would suggest rephrasing as "latter aspect".	The suggestion has been taken into consideration in the preparation of the revised paper.	First aspect
Line 170-173) Please consider splitting the phrase.	The sentence was rephrased.	See lines 217-222
Aline 170) Please clarify which is the regional system (Lombardia?).	The suggestion has been taken into consideration in the preparation of the revised paper.	Lombardy system
Line 179) I would suggest including the availability as first aspect in the list.	The suggestion has been taken into consideration in the preparation of the revised paper.	Regarding the second aspect, the costs and the availability of both secondary and primary raw materials and the quality of recycled materials are crucial aspects that influence the existence of a successful market sector of RAs
Line 185) I would suggest rephrasing embody with "include".	The suggestion has been taken into consideration in the preparation of the revised paper.	include
Line 186) Please clarify if the volume of RA is considered or, more likely, the amount of RA.	The suggestion has been taken into consideration in the preparation of the revised paper.	amount
Line 193) I would suggest rephrasing as "mixed and unsorted CDW".	The suggestion has been taken into consideration in the preparation of the revised paper.	mixed and unsorted CDW
Line 194) I would suggest using "rehabilitation" rather than restoration.	The suggestion has been taken into consideration in the preparation of the revised paper.	rehabilitation
Line 192-197) Please consider splitting the phrase and clarifying the last part.	Splitting has been considered whereas we think that it is not necessary to add other details not to make the paper too long: all the necessary additional information is reported in the cited reference.	See lines 259-265
Line 213-216) Please consider	The suggestion has been taken	In fact, most of the

splitting the phrase.	into consideration in the preparation of the revised paper.	indicators have positive values. The small benefits coming from the waste materials sorted in the strip
Line 217-218) This is the first time where the goals of the case study are clearly described, including the quality of the produced recycled aggregates. I would suggest including these consideration earlier in the paper.	The topic of the quality of the RAs has been already introduced in the methodology section. However, a more extensive explanation has been included in the revised paper.	see lines 238-249 and lines 257-267
Line 231-233) Please clarify which assumptions have been made for LQ selective demolition and to which type of construction the quality is related to (for example, are RA from LQ selective demolition used only for environmental rehabilitation and backfilling?).	A clarification has been added in the text.	See lines 257-267
Line 245) I would suggest rephrasing machineries with "equipment".	The suggestion has been taken into consideration in the preparation of the revised paper.	equipment
Line 299-303) Please consider splitting the phrase.	The suggestion has been taken into consideration in the preparation of the revised paper.	Moreover, since transportation looks as a crucial parameter, the waste should be delivered to the closest recycling facility, especially for the mineral CDW which is by far the most contributing material. A radius of 30 km provides a good margin to ensure net environmental and energetic benefits from selective demolition.

***Highlights**

- Selective demolition is perceived as essential for a sustainable built environment.
- A Life Cycle Assessment study was performed to verify if this is true.
- Selective demolition was compared to traditional demolition.
- Selective demolition is not always the best option.
- The results are heavily influenced by local conditions.

*Revised Manuscript (clean copy)
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Is selective demolition always a sustainable choice?

S. Pantini [a], L. Rigamonti [a,*]

[a] Politecnico di Milano, Department of Civil and Environmental Engineering, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

[*]corresponding author: Tel: +39 02 23996415. E-mail address: lucia.rigamonti@polimi.it

Abstract

Selective demolition is usually perceived as essential for a sustainable built environment since it aims to maximise the valorisation of constituent building materials and components giving them a new life. The successful diversion of construction materials from landfill and the extent of recovery of construction and demolition wastes as secondary raw materials depend on how the demolition work is executed, as well as on the logistic and economic aspects of the geographic context. The main goal of this study is to critically explore the sustainability of selective demolition practices versus traditional ones by addressing the environmental issues through the Life Cycle Assessment methodology. The key parameters that determine the environmental profile of a selective demolition project and their effects on the overall environmental balance were identified. Primary site-specific data supplied by the demolition companies involved in the demolition of a residential building located in Milan (Northern Italy) were used in the analysis. The results indicate that the environmental sustainability depends a lot on the characteristics of the building to be demolished as well as on the local markets for recycled materials. Moreover, the benefits from substituting primary raw materials can be overset by the increased impacts due to additional energy requirements of the selective demolition in comparison to the traditional one. Consequently, the environmental sustainability of selective demolition should be addressed on a case by case basis.

Keywords: construction and demolition waste; building; life cycle assessment; environmental assessment; demolition

1. Introduction

Selective demolition, also known as "construction in reverse" or "deconstruction", consists in a sequence of demolition activities to allow the separation and sorting of building components and valuable building materials such as metals, windows, doors, tiles, bricks, plasterboards, and so on (European Commission, 2016).

From a general point of view, selective demolition has several advantages over the traditional one, that are: i) increased diversion rate of Construction and Demolition Wastes (CDW) from landfill (Gálvez-Martos et al., 2018), and consequent land use preservation; ii) valorisation of waste as secondary raw materials consequently reducing the need of primary raw materials; iii) enhanced environmental protection both at local and global scale (Kibert et al., 2001) by reducing waste landfilling and the use of new materials; iv) reduction in overall demolition costs through landfill charge savings and revenues from the sale of secondary raw materials (Coelho and de Brito, 2011). All these aspects lead to the perception of selective demolition as absolutely essential for a sustainable built environment.

However, selective demolition still faces with significant challenges that might not be easily overcome. Indeed, existing buildings and building components have not been designed for dismantling or disassemble. In some context, like in Italy, the construction practices of buildings encompass the use of materials with surface coating or secondary finishing. The separation of the different components is currently almost not feasible from a technical and economical point of view (e.g. separation of concrete from bricks or mortar from bricks). The extent of materials separation also depends on the possibility of re-using the building components on site, on the local market for recycled materials and their competitiveness compared to primary raw materials as well as on political aspects, such as regulations, mandates, laws, and incentives in place (Duan et al., 2019).

The construction industry is mostly composed of small and medium enterprises, operating under a tight profit margin. Consequently, they do not take efforts in implementing re-use and recycle programs without an immediate economic profit. Higher disposal fees can succeed in adopting more eco-friendly waste management options but are not the only drivers. Moreover, selective demolition requires additional time, space and skilled labour that can be seen as constraint elements in some cases, leading traditional demolition to be preferred to selective demolition by many owners and contractors.

Hence, the environmental and economic viability of a selective demolition project should be evaluated prior to the demolition work on a case by case basis, having regard to the building-related specificity as well as to the context-related factors. The main goal of this study is to critically explore the sustainability of selective demolition activities in comparison to traditional ones through the Life Cycle Assessment (LCA) methodology. The LCA was selected for this purpose since it has become a well-accepted and widely adopted tool to investigate the environmental loads of buildings or construction projects, due to its integrated and holistic approach (Anand and Amor, 2017; Giani et al., 2015; Ortiz et al., 2009).

2. Methodology

This LCA study aims to understand how and to what extent the use of different demolition techniques can influence the performance of the system under study in terms of environmental and energetic loads. A real case study, i.e. the selective demolition of a residential building located in Milan (Northern Italy), has been considered.

According to ISO 14040 (2006), an LCA has four steps: 1. the goal and scope definition, in which the goal of the study, the functional unit, the system boundary, and the main assumptions are defined; 2. the life cycle inventory (LCI) analysis: this is an inventory of input/output data with regard to the system under study. It involves the collection of the data necessary to meet the goals of the study; 3. the life cycle impact assessment (LCIA): it is the third phase of the LCA and it aims

78 at understanding and evaluating the magnitude and significance of the potential environmental
79 impacts due to the resources consumption and the environmental emissions inventoried in step 3; 4.
80 the interpretation of the results: it is the final phase of the LCA in which the findings of the
81 inventory analysis and the impact assessment are evaluated in relation to the defined goal and scope
82 to reach conclusions and formulate recommendations.
83 In this case study, the functional unit (FU) is 1 m^2 of floor area, in line with other studies dealing
84 with the environmental assessment of buildings demolition (Anand and Amor, 2017; Hafner and
85 Schäfer, 2017; Ortiz et al. 2009; Vitale et al., 2016). The system boundaries include all the
86 processes involved in the strip out and demolition phases, e.g. the consumptions associated to the
87 use of the mechanical equipment and the generation of the different waste streams, their storage,
88 transportation and subsequent treatments. The system expansion approach was adopted to include
89 the avoided production and supply of primary raw materials that can be replaced by the use of
90 recycled materials. The LCA analysis was carried out using the SimaPro 8.5 software and the
91 ecoinvent 3.3 database for the background processes (e.g. Italian electricity mix). The ILCD 2011
92 Midpoint (EC JRC, 2011) was adopted for assessing the potential environmental impacts and the
93 Cumulative Energy Demand (CED) (Frischknecht et al., 2007) for the total energy consumption.
94 Besides the indicators of the ILCD and CED methods, another quantitative indicator estimating the
95 consumption of virgin mineral resources (mainly sand, gravel and gypsum) has been introduced, as
96 described in Borghi et al. (2018). Sensitivity and scenario analyses were performed to understand
97 the influence of different parameters on the sustainability of the demolition project and to increase
98 the reliability of the LCA outcome. The analyses addressed five parameters: the replacement of
99 primary raw materials with secondary raw materials by varying the quality of Recycled Aggregates
100 (RAs) and the market factor (i.e. the ratio between the amount of RAs sold and the total RAs
101 produced from CDW recycling in the Lombardy Region, as described in Borghi et al., 2018); the
102 total energy (electricity and fuel) requirement of demolition works; the waste transportation to the

CDW recycling facility; the amount of wastes generated and sorted and their management options (i.e. recycling vs disposal, incineration vs disposal).

2.1 Project site: description and inventory data

The selective demolition case study is a four-story residential building with an additional recent basement. The overall surface to be demolished is of 7,000 m^2 (total volume of about 10,000 m^3). The demolition works started in October 2018 and are expected to be concluded at the end of 2019. The initial decommissioning process had already been performed by an Italian construction firm, which manually removed all hazardous components and materials (e.g. asbestos), sanitary facilities (e.g. pipework, toilet) and technical building systems (e.g. heating, ventilation and air conditioning systems, elevator, lighting, furniture). Consequently, the building was empty when the selective demolition work has started. The project activities, assessed in the LCA study, encompass: i) soft-stripping i.e. the removal of non-structural construction elements (e.g. windows, doors, fixtures, internal glazing); ii) deconstruction of structural elements, i.e. the removal of partitions, substrates, etc. iii) demolition of the load-bearing parts. Three electric mini-excavators, a motofog, four diesel excavators, a skid steer loader (last generation vehicles) and an elevating platform were used in the demolition works, implying a total electricity and diesel consumption of 5.4 kWh/FU and 283.5 MJ/FU, respectively.

Data on the amount of waste materials produced during the soft stripping (i) were recorded and provided by the company, whereas the waste streams produced during the deconstruction of structural elements (ii) and demolition (iii) phases were estimated by projecting the field "partial" data up to the end of the demolition work. Specifically, the available measured data, which refer to the demolition of one floor, were multiplied by 4 as all the floors were similar. Alternatively, the assessment of the waste materials at a project level can be based on other methodologies, e.g. waste audits, Building Information Modelling - BIM, Generation Rate Calculation - GRC- models (European Commission, 2018; Wu et al., 2014). These models usually require for an inventory of

materials and building elements as well as information about the building construction techniques and its history to get accurate CDW estimations.

The total CDW generation rates for each waste category are reported in Table 1, together with the final destination and the transport distance associated to each step of their own recycling/disposal route. In all cases, CDW transportation occurred with Euro 6 trucks. Waste data indicate that the selective demolition allows to achieve a very high recovery efficiency: 98.5% of the total CDW generated was sent to recycling. On the contrary, the re-use of sorted components both on site and off site did not take place at all. CDW landfilling only accounted for about 28.5 t/FU. It comprises: the mixed non mineral CDW, mainly composed of unsorted packaging materials, textiles, paper and so on, with a very low recoverable value; the plastics, usually in the form of composite materials like cladding panels, roof or floor covering, membranes, etc., for which the disassembling and recycling still looks economically disadvantageous compared to direct landfilling; and the plasterboard panels from deconstruction of interior walls and ceilings, that are landfilled since no dedicated recycling plant exists in the Lombardy region.

Table 1 also reports the estimated rate of CDW generation in the case of a traditional demolition. This is an artificial scenario where the same analysed building is supposed to be demolished by applying traditional techniques in which mechanical devices (big diesel excavators) are used. Other demolition methods, such as those involving the use of explosives or suspended iron balls, may not be applied in this case study due to proximity to other buildings and limits set for the noise threshold. As pointed out by interviewing some demolition companies, even in the case of traditional demolition works, the current practices imply the prior removal of hazardous components that would otherwise contaminate the downstream waste leading to higher disposal fees. Consequently, the modelling of hazardous CDW management was not included in the system boundaries as it is common to all scenarios. Moreover, reinforcement bars are usually extracted from the crushed concrete structures by using excavator grapples, due to the high economic value of ferrous metals in the local market (200 €/t). The remaining bars (the separation at the demolition

site does not have an efficiency of 100%) together with all other building materials (wood, glass, plastics, exc.) are supposed to end up in the mixed inert CDW, which is assumed to be delivered to the same recycling facility of the selective demolition scenario. The overall energy consumption for the traditional demolition activities is of 0.2 kWh/FU and 311 MJ of diesel/FU. In the CDW recycling plant, since this mixed CDW is characterized by greater impurities than the one coming from the selective demolition, a more intensive manual sorting step is assumed prior to the common mechanical recycling process consisting in crushing, sieving and magnetic separation. The manual sorting is necessary to guarantee the compliance of RAs with the Italian quality requirements (Ministerial Communication n. 5205/2005 of the Italian Ministry of the Environment, Land and Sea) set for their use in road construction works. In fact, according to Borghi et al. (2018), on average, the amount of produced RAs corresponds to 99.4% of CDW entering the plant. The removed impurities mainly consist of ferrous metals (0.13%), wood and plastics (0.30%) and unrecoverable materials (0.17%). Taking into consideration for those removal efficiencies and the waste materials produced at the demolition site, the percentage composition of RAs was estimated to verify whenever or not it complies with the Italian standard requirements. The content of the following materials appeared as critical: wood content of 0.187% (limit value set by Ministerial Communication n. 5205/2005, all attachments: <0.1%); plastics content of 0.193% (limit value set by Ministerial Communication n. 5205/2005, all attachments: <0.1%); and gypsum content of 0.717%, that fails to meet even the least stringent limit (<0.6%) related to the uses in embankments and fillings (attachment C4 of the Ministerial Communication n. 5205/2005). The more intense manual sorting step was then modelled prior to the CDW recycling treatment to remove: 6.05 kg/m^2 of gypsum wastes, disposed in landfill (distance: 59 km - average between the distances of the two landfills in Lombardy that receive gypsum waste from the recycling plant); 1.65 kg/m^2 of wood, sent to another landfill site (distance: 27.5 km; Borghi et al., 2018); 1.77 kg/m^2 of plastics that are landfilled due to their dirty nature (distance: 35 km – same distance as in the selective demolition scenario). This step requires an additional operation time of the machineries used in handling and

moving the wastes within the sorting area (skid steer loader, buckets, and exc.). Thus, an increase in the diesel consumption was considered for CDW recycling in the traditional scenario compared to the selective one (0.87 l/t_{CDW} vs 0.64 l/t_{CDW}).

2.2 CDW management system and local markets for secondary raw materials

When sustainability of a demolition project has to be addressed, the available infrastructures and recycling technologies as well as the market demand of secondary materials must be taken into consideration to avoid possible overestimation of the benefits coming from the CDW recycling chains. As regards the first aspect, the analysis showed that the Lombardy system works efficiently with a total of 378 CDW recycling plants well-distributed over the territory. There are mostly semi-mobile plants fuelled by diesel that operate a primary crushing and metal separation, and optionally the removal of lightweight impurities and the final sieving into two or more dimensional classes. Plasterboard wastes are usually mixed in the CDW recycling facilities since there is no dedicated plant in operation at the current state in Lombardy (Borghi et al., 2018; Pantini et al., 2019). Despite the wide availability of infrastructures is expected to limit the transport distance within a radius of 30-50 km from the working site, in this case study, the CDW is transported for a longer distance (105 km) due to the commercial agreements between the demolition company and the CDW recycling plant. This aspect should be always addressed in order to avoid miss-computation on waste transportation which is recognized to greatly affect the environmental impact of such systems (Borghi et al., 2018; Blengini and Garbarino, 2010; Martinez et al., 2013).

Regarding the second aspect, the costs and the availability of both secondary and primary raw materials and the quality of recycled materials are crucial aspects that influence the existence of a successful market sector of RAs. All these aspects are strictly related to local peculiarities and conditions encompassing different areas related to people, policy, economy and technical aspects. In Lombardy, well-established recycling chains and local markets exist for metals, glass and wood whereas a significant spatial and temporal fluctuation in the demand of RAs was observed (Borghi

et al., 2018). This is mainly ascribed to the low-medium quality of RAs that limits the RAs use as filling material in environmental restoration/landscaping works (attachment C4 of the Ministerial Communication n. 5205/2005) or as unbound aggregate in embankments and sub-bases of roads, motorways or railways (attachments C1 and C2 of the Ministerial Communication n. 5205/2005, respectively). The more stringent criteria set for the RAs use in base layers (attachment C3 of the Ministerial Communication n. 5205/2005) are rarely satisfy mostly due to the presence of bricks and tiles in the CDW that cannot be removed through the simple mechanical processes applied in CDW recycling plants. And it is recognised that these materials are responsible for lowering the RAs resistance to fragmentation below the threshold values required in road bases, thus preventing this potential application. As regards the use of RAs in concrete production, very few cases were observed in the Lombardy region (Borghi et al., 2018), and only in lean concrete production. Hence, the environmental assessment should include considerations about the technical performance and the sold amount of RAs so that the avoided primary raw materials can be identified and quantified through appropriate replacement factors. A summary of avoided primary raw materials and replacement factors is shown in Table 2. It is worth noting that CDW from selective demolition has higher quality and can be used to produce RAs with better technical performance suitable for high-grade applications (such as in concrete production) in substitution of natural aggregates (NA: sand and gravel). In that case, if the market is well developed, the quality of RAs is not a limiting factor and, hence, the replacement factor is 1. In the baseline scenario of selective demolition (Selective demolition_HQ), it was assumed that 50% of RAs is suitable for high-grade applications (CDW-HQ) while the remaining 50% is low-quality RAs (CDW- LQ). On the contrary, in case of mixed and unsorted CDW originating from the traditional demolition (100% CDW- LQ), the quality of RAs limits their uses in low grade applications (rehabilitation, fillings, embankments, road sub-bases) and their market demand (average market factor for the whole region: 0.67). In this case, the RAs replace the natural soil (only excavation without processing) with a factor minor than 1, due to market and technical restrictions (more information in Borghi et al., 2018). Also, a worst case

scenario of selective demolition (Selective demolition_LQ) that implements the same RAs end-uses of the traditional one was analysed to test the effect of a lack of RAs demand for high-grade uses.

3. Results

The results from the impact assessment, reported in Table 3, show that for the analysed case study the selective demolition is not effective enough to produce net environmental and energetic savings. In fact, most of the indicators have positive values. The small benefits coming from the waste materials sorted in the strip out phase and then recycled do not lead to sufficiently large savings from the avoided extraction and processing of primary raw materials able to compensate the impacts associated with the demolition works, the waste transportation and the CDW recycling process.

Compared to traditional demolition, selective demolition performed in the case study (i.e. selective demolition with the production of High Quality RAs – Selective demolition_HQ) produces significant environmental improvements only for the climate change impact category (-48%), the energetic indicator (-64%), the mineral & fossil resource depletion impact category (-21%) and the mineral resource consumption indicator (-29%), mostly thanks to the recycling of glass, ferrous metals and CDW, respectively. On the other hand, there are relevant environmental burdens in the acidification, human toxicity, ecotoxicity, and eutrophication impact categories. The landfilling of plastics and gypsum wastes and aluminium recycling process are some of the contributions to this result.

When the aggregates from CDW recycling cannot be used in high grade applications due to the absence of a ready market (Selective demolition_LQ, Table 3), the selective demolition shows similar or even worse results than the traditional demolition scenario. The environmental advantages coming from waste materials sorting are thus frustrated. This result highlights the importance of including the effect of local market conditions for secondary and primary raw materials when the environmental sustainability of demolition projects has to be addressed (see also

the graphs on the first row of Figure 1). Only from the energetic point of view, the selective demolition looks always more beneficial than the traditional one, regardless the quality and final end-uses of the RAs. The more intensive use of diesel machines and electric equipment required in the selective demolition is indeed largely overcome by the energetic savings arising from the avoided extraction and processing of primary raw materials mainly due to iron and steel recycling and to the other materials sorted in the strip out phase. The latter contribution is null in case of traditional demolition leading to the higher energetic demand reported in Table 3.

Results from the sensitivity analyses are shown in Figure 1 and Figure 2: these graphs display the trends of the selected impact indicators related to each investigated system's parameter. The blue and yellow dots stand for the base case and worse case selective demolition scenarios, respectively; the black line represents the performance of the traditional demolition. The x-axis displays the percentage variation of the analysed parameter with respect to the value assigned in the baseline while the y-axis is the corresponding value of the impact indicator returned by the LCA. Results of the energetic indicator shown in Figure 1 and 2 demonstrate that the extent to which the selective demolition is energetically more convenient than the traditional one is strictly connected with the type and performances of the mechanical equipment as well as with the amount of iron and steel metals that can be sorted and recycled. As shown in Figure 1, the sustainability of selective demolition is higher when the additional energy requirement is supplied with electric equipment. In fact, if the total electricity consumption is increased by 50% of its initial value (from 5.4 kWh/FU to 8.1 kWh/FU), the performance of the base case selective demolition (Selective demolition_HQ) approaches those of the traditional scenario in the climate change impact category. However, only a 10% increase in the electricity consumption can frustrate the environmental advantages of the selective demolition in case of low quality RAs (yellow dots). From the energetic point of view (CED), the increment in the electricity requirements should be much higher (+300-400%) thanks to the larger margin originating from the avoided products (mainly steel). The turning point in case of diesel machineries is instead noticeably closer: an increment of 10% and 35% (value in the

baseline: 283.5 MJ/FU) is sufficient to lower the performance of selective demolition at the same level of traditional one in the climate change and energetic demand, respectively.

Other key points that determine the environmental sustainability of selective demolition are related to the type and amount of sorted materials and how they are handled (i.e. location and type of receiving facilities), as shown in Figure 2. Significant environmental improvements can be attained by increasing the recycled amount of iron and steel (Figure 2, graphs on the first row); a 20% increment of the baseline value (i.e. from 48 kg/FU to 57.6 kg/FU) leads to a net benefit in the climate change impact category and to a 90% reduction in the CED indicator. Structural steel thus appears as one of the most contributing material, as also observed by Buyle et al. (2018) and Vitale et al. (2017). Vitale et al. (2017) analysed the potential environmental impacts related to the selective demolition of a three-levels residential building located in the South of Italy by applying an attributional LCA. The results from the base case (83% materials recovery) underlined the dominant contribution of steel recycling in all the impact categories whereas the recycling of inert materials exhibited little environmental advantages. Also in the study of Ghose et al. (2017), most environmental benefits are associated with the recycling of aluminium and steel since these materials require energy intensive productions. Recycling of other materials, such as glass and concrete, can also contribute in reducing the environmental impacts in the global warming, photochemical ozone formation, acidification, abiotic depletion, and eutrophication impact categories. They also conclude that the potential environmental impact of the refurbishment work in New Zealand object of their analysis strongly depends on where the construction materials are produced and on the energy requirements and sources.

Waste transportation, and particularly the distance between the working site and the CDW recycling plant is by far the most influencing parameter, since the mixed CDW is the prevalent fraction generated during demolition. As shown in Figure 2 (second row), if the transport distance is reduced to 50 km (-52% of the baseline value on the x-axis) both the climate change and the energetic demand can be turned from burdens to benefits, thus improving the sustainability of the

311 selective demolition while lowering the influence of RAs quality and end-uses on the overall
312 results. Similarly, Martinez et al. (2013) found that waste transportation from the demolition work
313 to the treatment plant / final disposal and the fuel consumptions in demolition equipment and in the
314 treatment plants are the most relevant processes in a selective demolition scenario of a building in
315 the Spain context. In their study, 46% of CDW generated during the demolition of concrete
316 structures and the dismantling of metal and plastic parts, windows frames and doors is directly
317 recycled. 50% of CDW, coming from the demolition of partitions, is sent to treatment to recycle
318 ceramics, concrete, steel and gypsum while the remaining CDW is directly disposed in landfills.
319 Compared to the conventional demolition scenario, where all CDWs are landfilled, the selective
320 demolition allows for a reduction of environmental burden of 89% in global warming, 67% in
321 human toxicity and 49% in primary energy.
322 Among the waste management strategies (Figure 2, third row), the incineration of mixed plastic
323 instead of its landfilling, appears as the most effective from the energetic point of view (negative
324 indicator), followed by the recycling of gypsum waste (CED value close to zero). On the contrary,
325 incinerating the non-mineral mixed CDW seems to worsen the system performance in the climate
326 change impact category and in the energetic demand, since the system approaches the same results
327 as in the traditional demolition scenario.
328

329 **4. Discussion and conclusions**

330 Selective demolition is perceived as absolutely essential in improving the sustainability of the
331 building sector. Nonetheless, the evidence on the environmental superiority of selective demolition
332 practices compared to traditional ones appears highly uncertain due to the complexity and huge
333 influence of local features on such a system. In this research, a medium-size working site was
334 analysed taking as reference the geographic context of Lombardy region with the main objective of
335 pointing out general remarks when evaluating the sustainability of deconstruction project from a life
336 cycle perspective. The assessment of this case study showed that there are no significant

environmental benefits in selectively demolishing a building, compared to traditional demolition, if the sorted waste materials are not properly managed (e.g. maximization of recycling, minimization of transport distance) and a ready market does not exist for the use of the RAs in high grade applications. A particular attention should be paid in choosing the most appropriate destination for mixed non recoverable plastics and for gypsum based waste resulting from stripping and demolition works, which is in turn strictly related to the geographic context (e.g. availability of infrastructures and localization of the recycling plants). Moreover, since transportation looks as a crucial parameter, the waste should be delivered to the closest recycling facility, especially for the mineral CDW which is by far the most contributing material. A radius of 30 km provides a good margin to ensure net environmental and energetic benefits from selective demolition. Finally, the LCA results point out that the environmental convenience of the selective demolition project can be totally overturned depending on the additional energy requirements and the types of mechanical equipment involved in the works (e.g. electric equipment should be preferred instead of diesel one).

On the contrary, selective demolition looks always beneficial from an energetic point of view, to an extent that is strictly connected to the amount of iron and steel that can be sorted and recycled.

The results highlight the crucial importance of including the building characteristics as well as the context-related factors in the sustainability assessment of a building demolition project.

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Table 1. CDW generation from the selective demolition of the building under study in comparison to the traditional scenario, with the indication of the waste management routes and transport distances.

	SELECTIVE DEMOLITION (STRIP-OUT + DEMOL.)		TRADITIONAL DEMOLITION	
Waste Material	Waste generation [kg/m^2]	Treatment / disposal options, including transport distances [km]	Waste generation [kg/m^2]	Treatment / disposal options, including transport distances [km]
Mixed concrete, bricks, tiles ceramics (EWC[1] 170107)	26.8	CDW Recycling [8 km] *Output: 27 kg/m^2 of recycled aggregates*	-	
Wood (EWC 170201)	3.5	Storage [8 km] → Upgrading [30 km] → Recycling [88 km] *Output: particle board*	-	
Glass (EWC 170202)	7.3	Storage [8 km] → Upgrading [30 km] → Recycling [28 km] *Output: glass cullet*	-	
Plastics (EWC 170203)	9.4	Storage [8 km] → Landfill disposal [35 km]	-	
Aluminium (EWC 170402)	1.2	Storage & Upgrading [10 km] → Recycling in foundry [105 km] *Output: secondary aluminium*	-	
Iron and steel (EWC 170405)	48.0	4.8 kg: Storage [10 km] → Upgrading [35 km] → Recycling in steelmaking [80 km] 43.2 kg: Upgrading [77.4 km] → Recycling in steelmaking [43.1 km]	43.2	Upgrading [77.4 km] → Recycling in steelmaking [43.1 km] *Output: secondary steel*

		Output: secondary steel		
Plasterboards (EWC 170802)	13.6	Storage [8 km] → Landfill disposal (abroad) [560 km]	-	
Mixed inert materials (EWC 170904)	1,834.0	CDW Recycling [105 km] *Output: 1,823 kg/m^2 of recycled aggregates*	1,906.0	Sorting + CDW Recycling [105 km]. *Output: 6.0[3] kg/m^2 of gypsum to landfill [59 km]; 1.7[3] kg/m^2 of wood to landfill [27.5 km]; 2.3[3] kg/m^2 of mixed plastics to landfill 35 [km]; 1,885 kg/m^2 of recycled aggregates*
Mixed non inert materials (EWC 170904)[2]	5.5	Landfill disposal [8 km]	-	

411

412 [1] EWC = European Waste Code

413 [2] mixture of paper, cardboard, plastic, textiles not easily separable

414 [3] from the sorting step carried out at the CDW recycling facility; waste amounts are estimated so that the Italian legislation requirements set for the

415 use of recycled aggregates as unbound materials in embankments or sub-bases are met

416

417

418 Table 2. Sorting and recycling efficiencies of different CDW materials, avoided primary products
419 and replacement factors between secondary and primary materials assumed in the LCA modelling.

Waste fraction	Sorting efficiency	Recycling efficiency	Secondary product	Primary product	Replacement factor
Iron and steel	94%	88.1%	Liquid steel	Liquid steel	1 kg : 1 kg
Aluminium	95%	NP	Aluminium scraps[3]	Al 99.7	1 kg : 0.70 kg
Wood	90.7%	88.0%	Particle board	Plywood	1 m^3 : 0.6 m^3
Glass	94.7%	60.5%	Glass cullet	Packaging glass	1 kg : 1 kg
CDW - HQ[1]	NP	99.4%	Recycled aggregate - HQ[1]	Natural aggregates	1 kg : 1 kg[4]
CDW - LQ[2]	99.5%	99.4%	Recycled aggregate – LQ[2]	Natural soil	1 kg : 0.65 kg (sub-base) 1 kg : 0.58 kg (fillings)

420

421 NP = Not Performed step

422 [1] CDW with very low impurities originating from selective demolition; High Quality (HQ) recycled
423 aggregates can be produced and used in high-grade applications

424 [2] CDW with high impurities originating from traditional demolition; Low Quality (LQ) recycled
425 aggregates are produced and used in low-grade applications

426 [3] The recycling process of aluminium scraps was not included in the system boundaries as the
427 aluminium scraps, at the inlet of the furnace for the production of secondary aluminium, were
428 assumed to substitute the unalloyed Al99.7 at the inlet of the alloying process

429 [3] It is 1 kg : 0.67 kg in the case study, where the real situation of Lombardy region (i.e. market for
430 recycled aggregates not completely developed) is modelled (Borghi et al., 2018)

Table 3. Environmental and energetic performance associated with the selective demolition scenario, in case of High Quality (HQ) and Low Quality (LQ) recycled aggregates from CDW, in comparison with the traditional demolition scenario.

Impact category or Indicator	**Unit**	**Traditional demolition**	**Selective demolition_HQ[1]**	**Selective demolition_LQ**
Climate change	kg CO_2 eq	6.71	3.50	6.24
Ozone depletion	kg CFC-11 eq	1.19E-05	1.18E-05	1.22E-05
Human toxicity, non-cancer effects	CTUh	1.13E-05	1.94E-05	1.99E-05
Human toxicity, cancer effects	CTUh	1.50E-04	1.64E-04	1.64E-04
Particulate matter	kg PM2.5 eq	4.36E-02	4.41E-02	4.60E-02
Photochemical ozone formation	kg NMVOC eq	0.375	0.381	0.397
Acidification	molc H+ eq	0.440	0.632	0.651
Terrestrial eutrophication	molc N eq	1.50	1.47	1.54
Freshwater eutrophication	kg P eq	-6.76E-02	-7.80E-02	-7.77E-02
Marine eutrophication	kg N eq	0.130	0.152	0.158
Freshwater ecotoxicity	CTUe	4349.5	5100.6	5112.2
Water resource depletion	m3 water eq	0.716	0.782	0.791
Mineral & fossil resources deplet.	kg Sb eq	-5.94E-05	-7.18E-05	-3.58E-06
CED	MJ	303.3	109.2	155.4
Mineral Resource indicator (Sand and Gravel)	kg	-1198.6	-1545.7	-1172.8
Mineral Resource indicator (Gypsum)	kg	-0.112	-0.127	-0.126

[1] Replacement factor equal to 1 kg RA : 0.67 kg NA

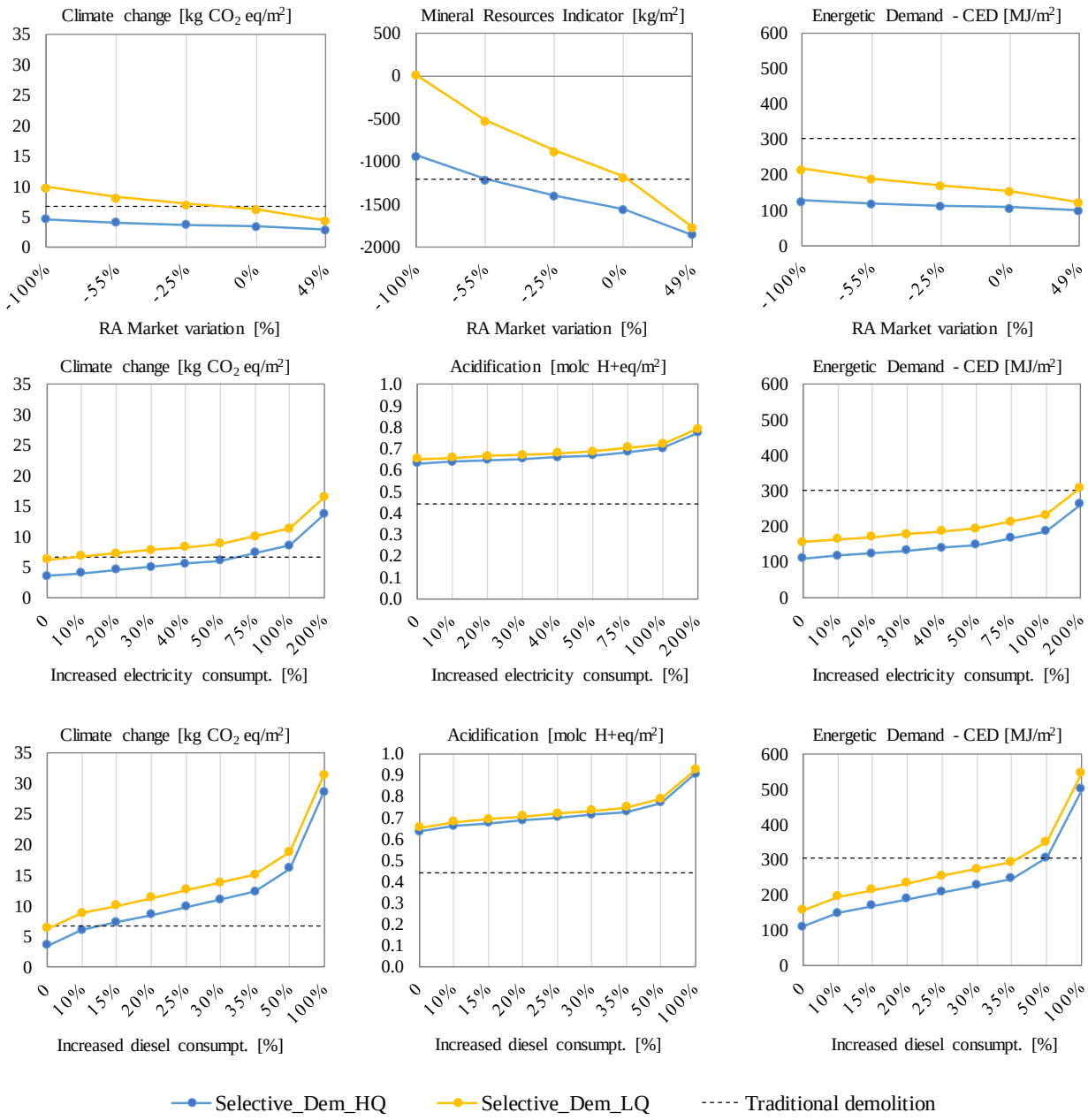
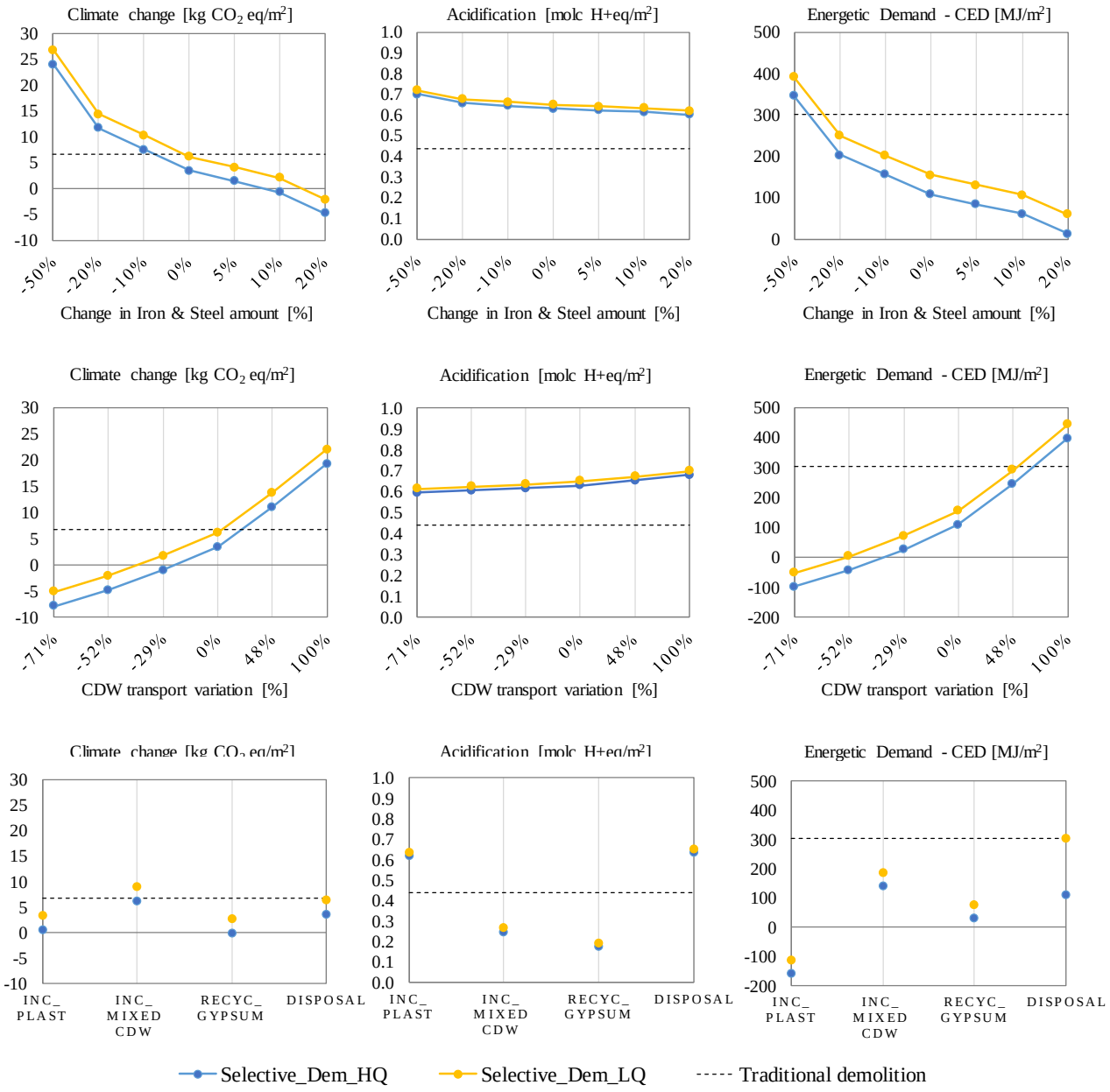


Figure 1. Trends of the most affected indicators by varying the market factor for the recycled aggregates and the electricity and diesel consumption of demolition works. X-axis: percentage variation of the system's parameter from the baseline value. Y-axis: LCA indicators related to traditional demolition (dotted black line), to selective demolition HQ - high grade applications of recycled aggregates (blue line) and to selective demolition LQ - low grade applications of recycled aggregates (yellow line).



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444 Figure 2. Trends of the most affected indicators by varying the amount of Iron & Steel, the transport
445 distance of CDW, and the waste management options for plastics, non-mineral mixed CDW and
446 gypsum. X-axis: percentage variation of the system's parameter from the baseline value. Y-axis:
447 LCA indicators related to traditional demolition (dotted black line), to selective demolition HQ -
448 high grade applications of recycled aggregates (blue line) and to selective demolition LQ - low
449 grade applications of recycled aggregates (yellow line).

*Revised Manuscript (With Track Changes)
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Is selective demolition always a sustainable choice?

S. Pantini [a], L. Rigamonti [a,*]

[a] Politecnico di Milano, Department of Civil and Environmental Engineering, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

[*]corresponding author: Tel: +39 02 23996415. E-mail address: lucia.rigamonti@polimi.it

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Abstract

Selective demolition is usually perceived as essential for a sustainable built environment since it ~~aims to~~aims to maximise the ~~harvest~~ valorisation of constituent building materials and components giving them a new life. The successful diversion of construction materials from landfill and the extent of ~~exploitation~~ recovery of construction and demolition wastes as secondary raw materials depend on how the demolition work is executed, as well as on the logistic and economic aspects of the geographic~~al~~ context. The main goal of this study is to critically explore the sustainability of ~~deconstruction~~ selective demolition practices versus traditional ones ~~demolition~~ by addressing the environmental issues through the Life Cycle Assessment methodology. The ~~identification of the~~ key parameters that ~~governing~~ determine the environmental profile of a selective ~~deconstruction~~ demolition project and their effects on the overall environmental balance ~~was~~ were identified. ~~done based on~~ Pprimary site-specific data supplied by the demolition companies involved in the ~~demolishing~~ demolition of a residential building located in Milan (Northern Italy) were used in the analysis. The results indicate that the environmental sustainability ~~is strictly dependent~~ depends a lot on the characteristics of the building to be demolished as well as on the local markets for ~~recovered~~ recycled materials. Moreover, ~~the~~ the benefits from substituting primary raw materials can be overset by the increased impacts due to additional energy requirements of the selective demolition in comparison to the traditional one. Consequently, ~~and, thus,~~the environmental sustainability of selective demolition ~~this~~ should be addressed on a case by case basis. ~~Tipping~~

~~points may exist for the analysed system, as the benefits from substituting primary~~ raw ~~materials can be overset by the increased impacts due to additional energy requirements of the selective demolition in comparison with the traditional one.~~

Keywords: construction and demolition waste; building; life cycle assessment; environmental assessment; demolition

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1. Introduction

Selective demolition, also known as "construction in reverse" or "deconstruction", consists in ~~the dismantling~~a sequence of demolition activities to allow the separation and sorting of ~~the~~ building components ~~to separate and sort out~~and valuable building materials such as metals, windows, doors, tiles, bricks, plasterboards, and so on (European Commission, 2016).

From a general ~~view~~point of view, selective demolition has several advantages over the traditional one, that are: i) increased diversion rate of Construction and Demolition Wastes (CDW) from landfill (Gálvez-Martos et al., 2018), and consequent land use preservation~~thus preserving scarce land for other uses~~; ii) ~~exploitation~~ valorisation of waste as secondary raw materials consequently reducing the need of primary raw materials~~virgin resources~~; iii) enhanced environmental protection both at local and global scale ~~locally and globally~~ (Kibert et al., 2001) by reducing waste landfilling and the use of new materials; iv) reduction in overall demolition costs through landfill charge savings and revenues from ~~selling~~ the sale of secondary raw materials (Coelho and de Brito, 2011). All these aspects lead to the perception of selective demolition as absolutely essential for a sustainable built environment.

However, ~~deconstruction~~ selective demolition still faces with significant challenges that might not be easily overcome. Indeed, existing buildings and building components have not been designed for dismantling or ~~disassembly~~disassemble. In some context, ~~as~~ like in Italy, the ~~building~~ construction practices of buildings encompass the use of materials with surface coating or secondary finishing.

The , for which the separation of the different components during by disassembly or the recycling is currently little almost not workable feasible from a technical and economical viewpoint of view (e.g. separation of concrete from bricks in partitioning elements or mortar from bricks). The extent of materials separation also depends on the possibility of re-using on site the building components on site, on the local market capacity for recycled materials and their competitiveness compared to virgin resources primary raw materials as well as on political aspects, such as regulations, mandates, laws, and incentives in place (Duan et al., 2019). Indeed, tThe construction industry is mostly made composed of mid/smallsmall and medium size enterprises, operating under a tight profit margin.; thus Consequently, they would do not take efforts in implementing re-use and recycle programs without an immediate economic profit. Higher disposal fees can succeed in adopting more eco-friendly waste management options but are not the only drivers. Moreover, selective demolitiondismantling and sorting requires additional time, space and skilled labour that can be seen as constraint elements in some cases, leading traditional demolition to be preferred over todeconstruction selective demolition by many owners and contractors.

Hence, the environmental and economic viability of a deconstruction selective demolition project should be evaluated prior to the demolition work on a case by case basis, having regard to the building-related specificity as well as to the context-related factors. The main goal of this study is to critically explore the sustainability of selective demolition activities in comparison to traditional ones through the Life Cycle Assessment (LCA) methodology. The LCA was selected for this purpose since it has become a well-accepted and widely adopted tool to investigate the environmental loads of buildings or more generally of construction projects, due to its integrated and holistic approach (Anand and Amor, 2017; Giani et al., 2015; Ortiz et al., 2009).

2. Methodology

This LCA study aims to understand how and to what extent the use of different demolition techniques can influence the performance of the system under analysis study in terms of

environmental and energetic loads. , by considering aA real case study, i.e. the selective demolition of a residential building located in Milan (Northern Italy), has been considered.

According to ISO 14040 (2006), an LCA has four steps: 1. the goal and scope definition, in which the goal of the study, the functional unit, the system boundary, and the main assumptions are defined; 2. the life cycle inventory (LCI) analysis: this is an inventory of input/output data with regard to the system under study. It involves the collection of the data necessary to meet the goals of the study; 3. the life cycle impact assessment (LCIA): it is the third phase of the LCA and it aims at understanding and evaluating the magnitude and significance of the potential environmental impacts due to the resources consumption and the environmental emissions inventoried in step 3; 4. the interpretation of the results: it is the final phase of the LCA in which the findings of the inventory analysis and the impact assessment are evaluated in relation to the defined goal and scope to reach conclusions and formulate recommendations.

In this case study, tThe selected functional unit (FU) is 1 m^2 of floor area, in line with other studies dealing with the environmental assessment of buildings demolition (Anand and Amor, 2017; Hafner and Schäfer, 2017; Ortiz et al. 2009; Vitale et al., 2016). The system boundaries include all the processes involved in the strip out and demolition phases, e.g. from the consumptions associated to the use of the mechanical equipment and, through the generation of the different waste flowsstreams, their storage, transportation and subsequent treatments, up to their outlet from the system as an emission (solid, liquid or gaseous) or as a secondary raw material. The system expansion approach was adopted to include the avoided production and supply of primary products raw materials that can be replaced by the use of recycled materials. The LCA analysis was carried out with using the SimaPro 8.5 software and the ecoinvent 3.3 database for the background processes (e.g. Italian electricity mix). The ILCD 2011 Midpoint (EC JRC, 2011) was adopted for assessing the potential environmental impacts and the Cumulative Energy Demand (CED) (Frischknecht et al., 2007) for the total energy consumption. Besides the indicators returned byof the ILCD and CED methods, another quantitative indicator estimating the consumption of virgin

mineral resources (mainly sand, gravel and gypsum) has been introduced, as ~~previously~~ described in Borghi et al. (2018). ~~Finally,~~ Sensitivity and scenario analyses were performed to understand the influence of different parameters on the sustainability of the demolition project~~, some sensitivity and scenario analyses were performed aimed at~~and to increas~~e~~ing~~ the reliability of the LCA outcome. The analyses addressed five parameters: the replacement of primary raw materials ~~between~~ with secondary raw materials ~~and primary raw materials~~ by varying the quality of Recycled Aggregates (RAs) and the market factor (i.e. the ratio between the amount of RAs sold and the total RAs produced from CDW recycling in the Lombardy Region, as described in Borghi et al., 2018); the total energy (electricity and fuel) requirement of demolition works; the waste transportation to the CDW recycling facility; the amount of wastes generated and sorted ~~at the site~~ and their management options (i.e. recycling vs disposal, incineration vs disposal).

2.1 Project site: description and inventory data

The ~~project site~~selective demolition case ~~under~~ study is a four-story residential building with an additional recent basement~~, of recent construction~~. The overall surface to be demolished is of 7,000 m^2~~, for a~~ (total volume of about 10,000 m^3). The demolition works started in October 2018 and are expected to be concluded ~~within the~~at the end of 2019. The initial decommissioning process had already been performed by an Italian construction firm, which ~~had~~ manually removed all hazardous components and materials (e.g. asbestos), sanitary facilities (e.g. pipework, toilet) and technical ~~building equipment~~building systems (e.g. heating, ventilation and air conditioning systems, elevator, lighting, furniture). ~~Thus~~Consequently, the building was empty when the selective demolition work has started. The project activities, assessed in the LCA study, encompass~~consist in~~: i) ~~the~~ soft-stripping i.e. the removal of ~~all~~ non-structural construction elements (e.g. windows, doors, fixtures, internal glazing~~, partitions~~); ii) ~~the structural~~ deconstruction of structural elements, i.e. the removal of partitions, substrates, etc. iii) ~~the~~ demolition of the load-bearing parts. Three electric mini-excavators, a motofog, four diesel excavators, a skid steer loader (last generation

vehicles) and an elevating platform were used in the demolition works, implying a total electricity and diesel consumption of 5.4 kWh/~~m~~^{2} FU and 283.5 MJ/~~m~~^{2}FU, respectively.

Data on the amount of waste materials produced during the soft stripping (i) were recorded and provided by the company, whereas the waste streams produced during the ~~structural~~ deconstruction of structural elements (ii) and demolition (iii) phases were estimated by projecting the field "partial" data ~~(corresponding to the completion of the 25% of the project)~~ up to the end of the demolition ~~step~~work. Specifically, the available measured data, which refer to the demolition of one floor, were multiplied by 4 ~~to obtaine the waste originated from steps (ii) and (iii)~~as all the floors were similar. Alternatively, the assessment of the waste materials at a project level can be based on other methodologies, e.g. waste audits, Building Information Modelling - BIM, Generation Rate Calculation - GRC- models (European Commission, 2018; Wu et al., 2014). These models usually require for an inventory of materials and building elements as well as information about the building construction techniques and its history ~~for~~to get accurate CDW estimations.

The total ~~waste~~ CDW generation rates for each waste category are reported in Table 1, together with the final destination~~s~~ and the transport distance~~s~~ associated to each step of their own recycling/disposal route.~~;~~ I~~i~~n all cases, ~~waste~~ CDW transportation occurred with Euro 6 trucks. Waste data indicate that the ~~deconstruction process~~selective demolition allows to achieve a very high recovery efficiency: 98.5% of the total CDW generated ~~waste~~ was sent to recycling. ~~Conversely~~On the contrary, the re-use of sorted components both on~~at~~ site and off site did not take place at all. ~~Waste~~ CDW landfilling only accounted for about 28.5 t/~~m~~^{2}FU.~~,~~ It~~and~~ comprises: the mixed non mineral CDW, mainly composed of unsorted packaging materials, textiles, paper and so on, with a very low recoverable value; the plastics, usually in the form of composite materials like cladding panels, roof or floor covering, membranes, etc., for which the disassembling and recycling still looks economically disadvantageous compared to direct landfilling; and the plasterboard panels from deconstruction of interior walls and ceilings, that are landfilled since no dedicated recycling plant exists in the Lombardy region.

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Table 1. Waste CDW generation from the selective demolition of the building under study in comparison to the traditional scenario, with the indication of the waste management routes and transport distances.

-	SELECTIVE DEMOLITION (STRIP-OUT + DEMOL.)		TRADITIONAL DEMOLITION	
Waste Material	Waste generation [kg/m²]	Destination and relative transport [km]	Waste generation [kg/m²]	Destination and relative transport [km]
Mixed concrete, bricks, tiles ceramics (EWC[1] 170107)	26.8	CDW Recycling [8 km] Output: 27 kg/m² of recycled aggregates	-	-
Wood (EWC 170201)	3.5	Storage [8 km] → Upgrading [30 km] → Recycling in particle board [88 km] Output: particle board	-	-
Glass (EWC 170202)	7.3	Storage [8 km] → Upgrading [30 km] → Recycling in cullet [28 km] Output: glass cullet	-	-
Plastics (EWC 170203)	9.4	Storage [8 km] → Landfill disposal [35 km]	-	-
Aluminium (EWC 170402)	1.2	Storage & Upgrading [10 km] → Recycling in foundry [105 km] Output: secondary aluminium	-	-
Iron and steel (EWC 170405)	48.0	4.8 kg: Storage [10 km] → Upgrading [35 km] → Recycling in steelmaking [80 km] 43.2 kg: Upgrading [77.4 km] → Recycling in steelmaking [43.1 km] Output: secondary steel	43.2	Upgrading [77.4 km] → Recycling in steelmaking [43.1 km] Output: secondary steel
Plasterboards (EWC 170802)	13.6	Storage [8 km] → Landfill disposal (abroad) [560 km]	-	
Mixed inert materials (EWC 170904)	1,834.0	CDW Recycling [105 km] Producing Output: 1,823 kg/m² of recycled aggregates	1,906.0	Sorting + CDW Recycling [105 km]. ProducingOutput: 6.0³ kg/m² of gypsum to landfill [59 km]; 1.7³ kg/m² of wood to landfill [27.5 km]; 2.3³ kg/m² of mixed plastics to landfill 35 [km]; 1,885 kg/m² of recycled aggregates

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Mixed non-inert materials (EWC 170904)[2]	5.5	Landfill disposal [8 km]	-	-

[1] EWC = European Waste Code

[2] mixture of paper, cardboard, plastic, textiles not easily separable

[3] from the sorting step carried out at the CDW recycling facility; waste amounts are estimated so that the Italian legislation requirements set for the use of recycled aggregates as unbound materials in embankments or sub-bases are met

Table 1 also reports the estimated rates of ~~wastes~~ CDW generation in the case of a traditional demolition.~~:~~ T~~t~~his is an ~~fictitious~~ artificial scenario where the same analysed building is supposed to be demolished ~~with~~ by applying traditional techniques in which ~~using~~ mechanical devices (~~(~~big diesel excavators)~~}~~ are used. Other demolition methods, such as those involving the use of explosives or suspended iron balls, may not be applied in this case study due to proximity to other buildings and limits set for the noise threshold. As pointed out by interviewing some demolition companies, even in the case of traditional demolition works, the current practices imply the prior removal of hazardous components that would otherwise contaminate the downstream waste leading to higher disposal fees. ~~So~~Consequently, the modelling of hazardous ~~waste~~ CDW management was not included in the system boundaries ~~since~~ as it is common to all scenarios. Moreover, ~~usually,~~ reinforcement bars are usually extracted from the crushed concrete structures by using excavator grapples, due to the high economic value ~~(200 €/t)~~ of ferrous metals in the local market (200 €/t) ~~and the little efforts required~~. The remaining bars (the separation at the demolition site does not have an efficiency of 100%) together with ~~All~~ all other building materials (wood, glass, plastics, exc.~~...~~) are supposed to end up ~~forming~~ in the mixed inert CDW, ~~that~~ which is assumed to be delivered to the same recycling facility ~~as the one assumed in~~of the selective demolition scenario. The overall energy consumption for the traditional demolition activities~~y~~ is of 0.2 kWh/FU and 311 MJ of diesel/FU ~~per functional unit~~. In the CDW recycling plant, since this mixed ~~waste~~ CDW is characterized by greater impurities than the one coming from the selective demolition, a more intensive manual sorting step is assumed prior to the common mechanical recycling process consisting in crushing, sieving and magnetic separation. The manual sorting~~is~~ is necessary to guarantee the compliance of RAs with the Italian quality requirements (Ministerial Communication n. 5205/2005 of the Italian Ministry of the Environment, Land and Sea) set for their use in road construction works ~~(Circular n. 5205/2005 of the Italian Ministry of the Environment, Land and Sea)~~. In fact, ~~the common CDW recycling process, considering the currently implemented technologies, is not efficient enough in removing all light impurities. A~~according to Borghi et al.

(2018), on average, the amount of produced RAs corresponds to 99.4% of CDW entering the plant.~~:~~ T~~t~~he removed impurities mainly consist of ferrous metals (0.13%), wood and plastics (0.30%) and unrecoverable materials (0.17%). Taking into consideration for those removal efficiencies and the waste materials produced at the demolition site, the percentage composition of RAs was estimated ~~in order~~ to verify whenever or not it complies with the Italian standard requirements. The content of the following material~~s contents~~ appeared as critical: wood content of 0.187% (limit value set by ~~Circular~~Ministerial Communication n. 5205/2005, all attachments: <0.1%); plastics content of 0.193% (limit value set by Ministerial Communication~~Circular~~ n. 5205/2005, all attachments: <0.1%); and gypsum content of 0.717%, that fails to meet even the least stringent limit (<0.6%) related to the uses in embankments and fillings (attachment C4 of the Ministerial Communication~~Circular~~ n. 5205/2005 ~~<0.6%~~). The more intense manual sorting step was then modelled prior to the CDW recycling treatment to remove: 6.05 kg/m^2 of gypsum wastes, disposed ~~of~~ in landfill (distance: 59 km - average between the distances of the two landfills in Lombardy that receive gypsum waste from the recycling plant); 1.65 kg/m^2 of wood, sent to another landfill site (distance: 27.5 km; Borghi et al., 2018); 1.77 kg/m^2 of plastics that are landfilled due to their dirty nature (distance: 35 km – same distance as in the selective demolition scenario). This ~~pre-sorting~~ step requires an additional operation time of the machineries used in handling and moving the wastes within the sorting area (skid steer loader, buckets, and ~~...).~~ exc.). Thus, an increase in the diesel consumption was considered for CDW recycling in the traditional scenario compared to the selective one (0.87 l/t$_{CDW}$ vs 0.64 l/t$_{CDW}$).

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2.2 CDW~~Waste~~ management system and local markets for~~of~~ secondary raw materials

When sustainability of a demolition project has to be addressed, the available infrastructures and recycling technologies as well as the market demand of secondary materials must be taken into consideration to avoid possible overestimation of the benefits coming from the ~~waste~~ CDW recycling chains. As regards the ~~former~~ first aspect, the analysis ~~revealed~~ showed that the ~~regional~~

Lombardy system works efficiently with a total of 378 CDW recycling plants well-distributed over the territory.~~;~~ T~~t~~here are mostly semi-mobile plants fuelled by diesel ~~operating~~that operate a primary crushing and metal separation, and optionally the removal of lightweight impurities and the final sieving into two or more dimensional classes. ~~; the only exception exists~~Conversely, ~~for~~ P~~p~~lasterboard wastes are usually mixed in the CDW recycling facilities ~~cannot be recycled~~ since~~,~~ ~~since~~ there is no dedicated plant in operation at the current state in Lombardy ~~and are usually mixed in the CDW recycling facilities~~ (Borghi et al., 2018; Pantini et al., 2019). Despite the wide availability of infrastructures is expected to limit the transport distance within a radius of 30-50 km from the working site, in this case study, the CDW is transported for a longer distance (105 km) due to the commercial agreements between the demolition company and the CDW recycling plant. This aspect should be always addressed in order to avoid miss-computation on waste transportation which is recognized to greatly affect the environmental impact of such systems (Borghi et al., 2018; Blengini and Garbarino, 2010; Martinez et al., 2013).

Regarding the ~~latter~~ second aspect, the costs and the availability of both secondary and primary raw materials and the quality of recycled materials ~~, the costs and the availability of both secondary and primary resources~~ raw materials are crucial aspects that influenc~~i~~e~~ng~~ the ~~establishment~~ existence of a successful market sector of RAs. All these aspects are strictly related to local peculiarities and conditions encompassing different areas related to people, policy, economy and technical aspects. In Lombardy, well-established recycling chains and local markets exist for metals, glass and wood whereas a significant spatial and temporal fluctuation in the demand of RAs was observed (Borghi et al., 2018). This is mainly ascribed to the low-medium quality of RAs that limits the RAs use as filling material in environmental restoration/landscaping works (attachment C4 of the Ministerial Communication~~Circular~~ n. 5205/2005) or as unbound aggregate in embankments and sub-bases of roads, motorways or railways (attachments C1 and C2 of the Ministerial Communication~~Circular~~ n. 5205/2005, respectively). The more stringent criteria set for the RAs use in base layers (attachment C3 of the Ministerial Communication~~Circular~~ n. 5205/2005) are rarely satisfy mostly due to the

presence of bricks and tiles in the CDW that cannot be removed through the simple mechanical processes applied in CDW recycling plants. And it is recognised that these materials are responsible for lowering the RAs resistance to fragmentation below the threshold values required in road bases, thus preventing this potential application. As regards the use of RAs in concrete production, very few cases were observed in the Lombardy region (Borghi et al., 2018), and only in lean concrete production. Hence, t~~T~~he environmental assessment should ~~embody~~ include considerations about the technical performance and the sold ~~volume~~ amount of RAs so that the avoided primary ~~products~~ raw materials can be identified and quantified through appropriate replacement factors. A summary of avoided primary ~~products~~ raw materials and replacement factors is shown in Table 2. It is worth noting that CDW from selective demolition ~~have~~ has higher quality and can be used to produce ~~turned in~~ RAs with better technical performance ~~to be used~~suitable for ~~in~~ high-grade applications (such as in concrete production) in substitution of natural aggregates (NA: sand and gravel). In that case, if the market is well developed, the quality of ~~recycled materials~~RAs is not a limiting factor and, hence, the replacement factor is 1. In the baseline scenario of selective demolition (Selective demolition_HQ), it was assumed that 50% of RAs is suitable for high-grade applications (CDW-HQ) while the remaining 50% is low-quality RAs (CDW- LQ). ~~Conversely~~On the contrary, in case of ~~dirty~~ mixed and unsorted CDW originating from the traditional demolition (100% CDW- LQ), the ~~poor~~ quality of RAs limits their uses in low grade applications (~~restoration~~rehabilitation, fillings, embankments, road sub-bases) and their market demand (average market factor for the whole region: 0.67).~~;~~ ~~I~~in this case, the RAs replace the natural soil (only excavation without processing) with a factor minor than 1, due to market and technical restrictions (more information in Borghi et al., 2018). Also, a worst case scenario of selective demolition (Selective demolition_LQ) that implements the same RAs end-uses of the traditional one was analysed to test the effect of a lack of RAs demand for high-grade uses.

Table 2. Sorting and recycling efficiencies of different waste CDW materials, avoided primary products and replacement factors between secondary and primary materials assumed in the LCA modelling.

Waste fraction	Sorting efficiency	Recycling efficiency	Secondary product	Primary product	Replacement factor
Iron and steel	94%	88.1%	Liquid steel	Liquid steel	1 kg : 1 kg
Aluminium	95%	83.5%	Aluminium scraps	Al 99.7	1 kg : 0.70 kg
Wood	90.7%	88.0%	Particle board	Plywood	1 m^3 : 0.6 m^3
Glass	94.7%	60.5%	Glass cullet	Packaging glass	1 kg : 1 kg
CDW - HQ[1]	NP	99.4%	Recycled aggregate - HQ[1]	Natural aggregates	1 kg : 1 kg[3]
CDW - LQ[2]	99.5%	99.4%	Recycled aggregate - LQ[2]	Natural soil	1 kg : 0.65 kg (sub-base) 1 kg : 0.58 kg (fillings)

NP = Not Performed step

[1] CDW with very low impurities originating from selective demolition; High Quality (HQ) recycled aggregates can be produced and used in high-grade applications

[2] CDW with high impurities originating from traditional demolition; Low Quality (LQ) recycled aggregates are produced and used in low-grade applications

[3] It is 1 kg : 0.67 kg in the case study, where the real situation of Lombardy region (i.e. market for recycled aggregates not completely developed) is modelled (Borghi et al., 2018)

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3. Results

The results from the impact assessment, reported in Table 3, showed that for the analysed case study the selective demolition is not effective enough to produce net environmental and energetic savings. In fact, most of the indicators present have positive values. Tsince the little small benefits coming from the waste materials sorted in the strip out phase and thereafter then recycled do not lead to sufficiently large savings from the avoided extraction and processing of primary productions

raw materials able to compensate the impacts associated with the demolition works, the waste transportation and the CDW recycling processes.

Compared to the traditional demolition, the selective demolition performed in the real case study (i.e. selective demolition with the production of High Quality RAs – Selective demolition_HQ) produces significant environmental improvements only for the climate change impact category (-48%), the energetic indicator (-64%), the mineral & fossil resource depletion impact category (-21%) and the mineral resource consumption indicator (-29%), mostly thanks to the recycling of glass, ferrous metals and CDW, respectively. On the other hand, there are relevant environmental burdens arise in the acidification, and human toxicity, ecotoxicity, and eutrophication impact categories. , mainly ascribed to The landfilling of plastics and gypsum wastes and to the aluminium recycling process are some of the contributions to this result.

When the aggregates from CDW recycling cannot be used in high grade applications due to the absence of a ready market (Selective demolition_LQ, Table 3), It is interesting to note that the selective demolition shows results similar or even worse results and than the traditional demolition scenario. The s exhibit very similar results when the aggregates from CDW recycling cannot be used in high grade applications due to the absence of a ready market (Selective demolition_LQ, Table 3), thus nullifying the environmental advantages coming from waste materials sorting are thus frustrated. This result hence highlights the importance of including the effect of local market conditions for secondary and primary products raw materials when the environmental sustainability of demolition projects has to be addressed (see also the graphs on the first row line of Figure 1).

Table 3. Environmental and energetic performance associated with the selective demolition scenario, in case of High Quality (HQ) and Low Quality (LQ) recycled aggregates from CDW, in comparison with the traditional demolition scenario.

Impact category	Unit	Traditional demolition	Selective demolition_HQ[1]	Selective demolition_LQ

Climate change	kg CO_2 eq	6.71	3.50	6.24
Ozone depletion	kg CFC-11 eq	1.19E-05	1.18E-05	1.22E-05
Human toxicity, non-cancer effects	CTUh	1.13E-05	1.94E-05	1.99E-05
Human toxicity, cancer effects	CTUh	1.50E-04	1.64E-04	1.64E-04
Particulate matter	kg PM2.5 eq	4.36E-02	4.41E-02	4.60E-02
Photochemical ozone formation	kg NMVOC eq	0.375	0.381	0.397
Acidification	molc H+ eq	0.440	0.632	0.651
Terrestrial eutrophication	molc N eq	1.50	1.47	1.54
Freshwater eutrophication	kg P eq	6.76E-02	7.80E-02	7.77E-02
Marine eutrophication	kg N eq	0.130	0.152	0.158
Freshwater ecotoxicity	CTUe	4349.5	5100.6	5112.2
Water resource depletion	m3 water eq	0.716	0.782	0.791
Mineral & fossil resources deplet.	kg Sb eq	5.94E-05	7.18E-05	3.58E-06
CED	MJ	303.3	109.2	155.4
Mineral Resource indicator				
Sand and Gravel	kg	-1198.6	-1545.7	-1172.8
Gypsum	kg	-0.112	-0.127	-0.126

[1] Replacement factor equal to 1 kg RA : 0.67 kg NA

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Only from the energetic point of view, the selective demolition looks always more beneficial than the traditional one, regardless the quality and final end-uses of the RAs. The more intensive use of diesel machines and electric ~~machineries~~ equipment required in the selective demolition is indeed largely overcome by the energetic savings arising from the avoided extraction and processing of primary raw materials ~~avoided primary productions~~ mainly due to iron and steel ~~recovery~~ recycling and to the other materials sorted in the strip out phase. The latter contribution is null in case of traditional demolition leading to the higher energetic demand reported in Table 3.

Results from the sensitivity analyses are shown in Figure 1 and Figure 2: these graphs display the trends of the selected impact indicators related to each investigated system's parameter. The blue and yellow ~~points~~dots stand for the base case and worse case selective demolition scenarios, respectively; the black line represents the performance of the traditional demolition. The x-axis displays the percentage variation of the analysed parameter with respect to the value assigned in the baseline while the y-axis is the corresponding value of the impact indicator returned by the LCA~~.~~. ~~Indeed~~Results of the energetic indicator shown in Figure 1 and 2 demonstrate that~~,~~ the extent to which the selective demolition is energetically more convenient than the traditional one ~~appears~~ is strictly connected with the type and performances of the mechanical equipment as well as with the amount of iron and steel metals that can be sorted and ~~recovered~~recycled. As shown in Figure 1, the sustainability of selective demolition is higher when the additional energy requirement ~~for the deconstruction dismantling activities~~ is supplied with electric ~~machineries~~equipment. In fact, ~~only when~~if the total electricity consumption is increased by 50% of its initial value (from 5.4 kWh/~~m~~^{2} FU to 8.1 ~~5.4~~ kWh/~~m~~^{2}FU), the performance~~s~~ of the base case selective demolition (Selective demolition_HQ) approache~~s~~ those of the traditional scenario~~-~~ in the climate change impact category. ~~and,~~ However, only a 10% increase in the electricity consumption can frustrate the environmental advantages of the selective demolition in case of low quality RAs (yellow ~~points~~dots). F~~-~~rom the energetic point of view (CED), the increment in the electricity requirements should be much higher (+300-400%) thanks to the larger margin originating from the avoided products (mainly steel). The

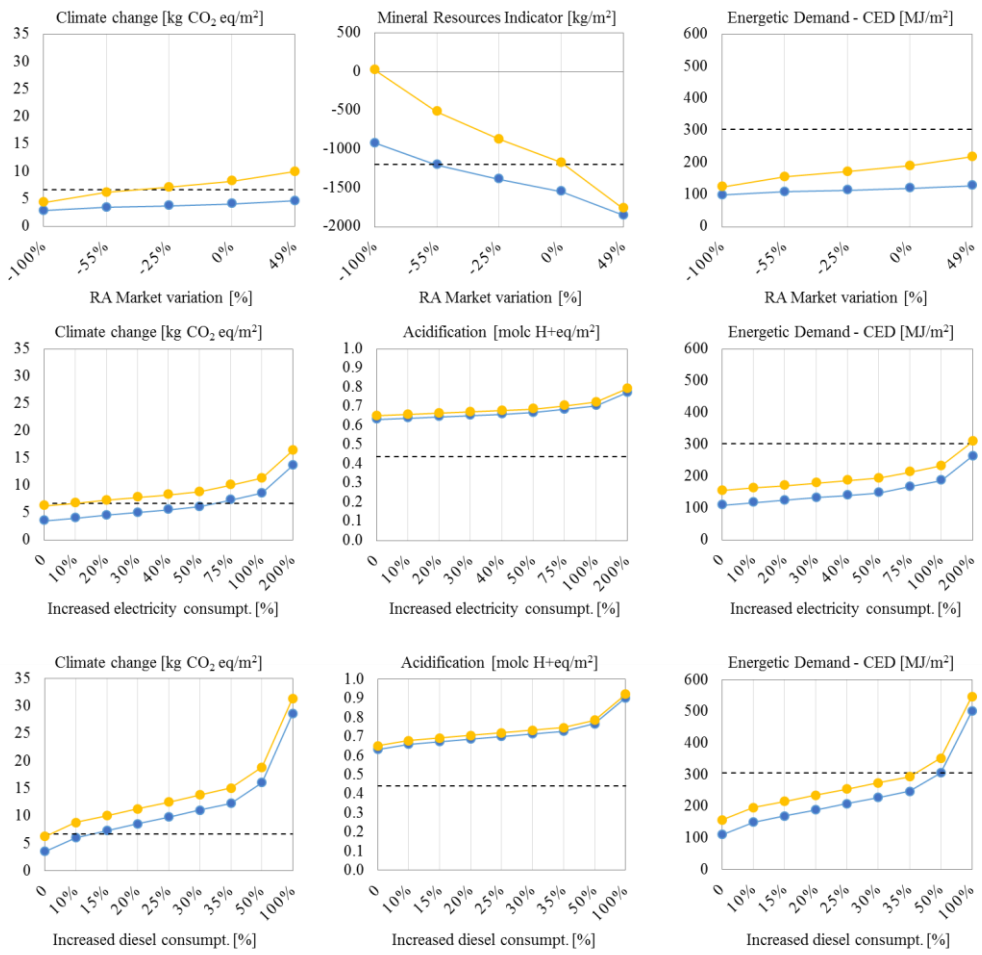
turning point in case of diesel machineries is instead noticeably closer: an increment of 10% and 35% (value in the baseline: 283.5 MJ/~~m~~^{2}FU) is sufficient to lower the performance of selective demolition at the same level of traditional one in the climate change and energetic demand, respectively.

Other key points ~~governing~~ that determine the environmental sustainability of selective demolition are related to the type and amount of sorted materials and how they are handled (i.e. location and type of receiving facilities), as shown in Figure 2. Significant environmental improvements can be attained by increasing the ~~recovered~~ recycled amount of iron and steel (Figure 2, graphs on the first ~~line~~row); a 20% increment of the baseline value (i.e. from 48 kg/~~m~~^{2} FU to 57.6 kg/~~m~~^{2}FU) leads to a net benefit in the climate change impact category and to a 90% reduction in the CED indicator. Structural steel thus appears as one of the most contributing material, as also observed by Buyle et al. (2018) and Vitale ~~a~~et al. (2017). Vitale et al. (2017) analysed the potential environmental impacts related to the selective demolition of a three-levels residential building located in the South of Italy by applying an attributional LCA. The results from the base case (83% materials recovery) underlined the dominant contribution of steel recycling in all the impact categories whereas the recycling of inert materials exhibited little environmental advantages. Also in the study of Ghose et al. (2017)~~-~~, most environmental benefits are associated with the recycling of aluminium and steel since these materials require energy intensive productions. Recycling of other materials, such as glass and concrete, can also contribute in reducing the environmental impacts in the global warming, photochemical ozone formation, acidification, abiotic depletion, and eutrophication impact categories. They also conclude that the potential environmental impact of the refurbishment work in New Zealand object of their analysis strongly depends on where the construction materials are produced and on the energy requirements and sources.

Waste transportation, and particularly the distance between the working site and the CDW recycling plant is by far the most influencing parameter, since the mixed CDW is the prevalent fraction generated during demolition. As shown in Figure 2 (second ~~line~~row), if the transport distance is

reduced to 50 km (-52% of the baseline value on the x-axis) both the climate change and the energetic demand can be turned from burdens to benefits, thus improving the sustainability of the selective demolition while lowering the influence of RAs quality and end-uses on the overall results. Similarly, Martinez et al. (2013) found that waste transportation from the demolition work to the treatment plant / final disposal and the fuel consumptions in demolition equipment and in the treatment plants are the most relevant processes in a selective demolition scenario of a building in the Spain context. In their study, 46% of CDW generated during the demolition of concrete structures and the dismantling of metal and plastic parts, windows frames and doors is directly recycled. 50% of CDW, coming from the demolition of partitions, is sent to treatment to recycle ceramics, concrete, steel and gypsum while the remaining CDW is directly disposed in landfills. Compared to the conventional demolition scenario, where all CDWs are landfilled, the selective demolition allows for a reduction of environmental burden of 89% in global warming, 67% in human toxicity and 49% in primary energy.

Among the waste management strategies (Figure 2, third ~~line~~row), the incineration of mixed plastic instead of its landfilling, appears as the most effective from the energetic point of view (negative indicator), followed by the recycling of gypsum waste (CED value close to zero). ~~Conversely~~On the contrary, incinerating the non-mineral mixed CDW seems to worsen the system performance in the climate change impact category and in the energetic demand, since the system approaches the same results as in the traditional demolition scenario.



~~Figure 1. Trends of the most affected indicators by varying the market factor for the recycled aggregates and the electricity and diesel consumption of demolition works, for the analysed scenarios: traditional demolition (dotted black line); selective demolition HQ – high grade applications of recycled aggregates (blue line); selective demolition LQ – low grade applications of recycled aggregates (yellow line).~~

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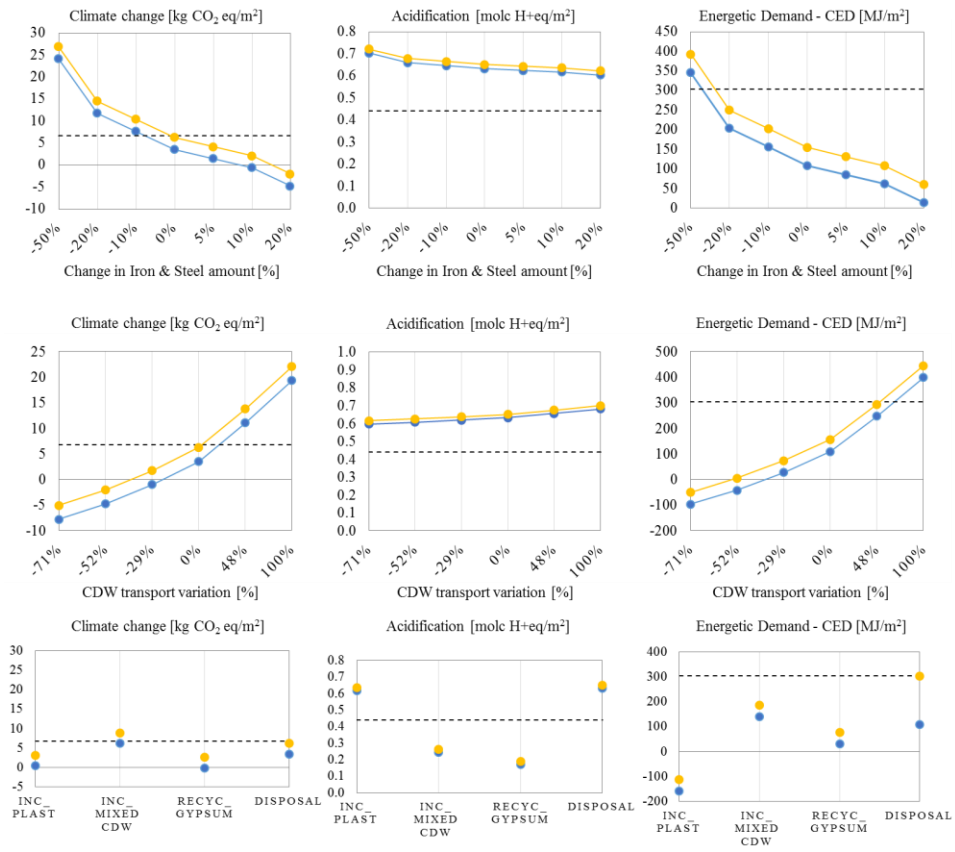

~~Figure 2. Trends of the most affected indicators by varying the amount of Iron & Steel, the transport distance of CDW, and the waste management options for plastics, non-mineral mixed CDW and gypsum, for the analysed scenarios: traditional demolition (dotted black line); selective demolition HQ – high grade applications of recycled aggregates (blue line); selective demolition LQ – low grade applications of recycled aggregates (yellow line).~~

4. Discussion and conclusions

Selective demolition is perceived as absolutely essential in improving the sustainability of the building sector. Nonetheless, the evidence on the environmental superiority of ~~deconstruction~~

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selective demolition practices compared to traditional ones appears highly uncertain due to the complexity and huge influence of local ~~peculiarities~~ features on such a system. In this research, a medium-size working site was analysed taking as reference the geographic~~al~~ context of Lombardy region with the main objective of pointing out general remarks when evaluating the sustainability of deconstruction project from a life cycle perspective. ~~For this case study, T~~the assessment of this case study ~~revealed~~ showed that there are no significant environmental benefits in selectively demolishing a building, compared to traditional demolition, if the sorted waste materials are not properly managed (e.g. maximization of recycling~~/recovery~~, minimization of transport distance) and a ready market does not exist for the use of the RAs in high grade applications. A particular attention should be paid in choosing the most appropriate destination for mixed non recoverable plastics and for gypsum based waste resulting from stripping and demolition works, which is in turn strictly related to the geographic~~al~~ context (e.g. availability of infrastructures and localization of the recycling plants). Moreover, since ~~waste~~ transportation looks as a crucial parameter, the waste should be delivered to the closest recycling facility, especially for the mineral CDW which is by far the most contributing material.~~:~~ A~~a~~ radius of 30 km provides a good margin to ensure net environmental and energetic benefits from selective demolition. Finally, the LCA results point out that the environmental convenience of the selective demolition project can be totally overturned depending on the additional energy requirements and the types of mechanical equipment involved in the works (e.g. electric ~~machineries~~ equipment should be preferred instead of diesel ~~machineries~~one).

~~Conversely~~On the contrary, selective demolition looks always beneficial from an energetic point of view, to an extent that is strictly connected to the amount of iron and steel that can be sorted and ~~recovered~~recycled.

~~Overall, t~~The results highlight the crucial importance of including the building characteristics as well as the context-related factors in the sustainability assessment of a building demolition project.

Acknowledgements

We thank the operators of the demolition activities and of the recycling plants that provided the data for the LCA and Michela Ruggeri for the support in their elaboration.

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Table 1. CDW generation from the selective demolition of the building under study in comparison to the traditional scenario, with the indication of the waste management routes and transport distances.

	SELECTIVE DEMOLITION (STRIP-OUT + DEMOL.)		TRADITIONAL DEMOLITION	
Waste Material	Waste generation [kg/m^2]	Treatment / disposal options, including transport distances [km]	Waste generation [kg/m^2]	Treatment / disposal options, including transport distances [km]
Mixed concrete, bricks, tiles ceramics (EWC[1] 170107)	26.8	CDW Recycling [8 km] *Output: 27 kg/m^2 of recycled aggregates*	-	-
Wood (EWC 170201)	3.5	Storage [8 km] → Upgrading [30 km] → Recycling [88 km] *Output: particle board*	-	-
Glass (EWC 170202)	7.3	Storage [8 km] → Upgrading [30 km] → Recycling [28 km] *Output: glass cullet*	-	-
Plastics (EWC 170203)	9.4	Storage [8 km] → Landfill disposal [35 km]	-	-
Aluminium (EWC 170402)	1.2	Storage & Upgrading [10 km] → Recycling in foundry [105 km] *Output: secondary aluminium*	-	-
Iron and steel (EWC 170405)	48.0	4.8 kg: Storage [10 km] → Upgrading [35 km] → Recycling in steelmaking [80 km] 43.2 kg: Upgrading [77.4 km] → Recycling in steelmaking [43.1 km]	43.2	Upgrading [77.4 km] → Recycling in steelmaking [43.1 km] *Output: secondary steel*

		Output: secondary steel		
Plasterboards (EWC 170802)	13.6	Storage [8 km] → Landfill disposal (abroad) [560 km]	-	
Mixed inert materials (EWC 170904)	1,834.0	CDW Recycling [105 km] *Output: 1,823 kg/m^2 of recycled aggregates*	1,906.0	Sorting + CDW Recycling [105 km]. *Output:* *6.0[3] kg/m^2 of gypsum to landfill [59 km];* *1.7[3] kg/m^2 of wood to landfill [27.5 km];* *2.3[3] kg/m^2 of mixed plastics to landfill 35 [km];* *1,885 kg/m^2 of recycled aggregates*
Mixed non inert materials (EWC 170904)[2]	5.5	Landfill disposal [8 km]	-	

[1] EWC = European Waste Code

[2] mixture of paper, cardboard, plastic, textiles not easily separable

[3] from the sorting step carried out at the CDW recycling facility; waste amounts are estimated so that the Italian legislation requirements set for the use of recycled aggregates as unbound materials in embankments or sub-bases are met

Table 2. Sorting and recycling efficiencies of different CDW materials, avoided primary products and replacement factors between secondary and primary materials assumed in the LCA modelling.

Waste fraction	Sorting efficiency	Recycling efficiency	Secondary product	Primary product	Replacement factor
Iron and steel	94%	88.1%	Liquid steel	Liquid steel	1 kg : 1 kg
Aluminium	95%	NP	Aluminium scraps[3]	Al 99.7	1 kg : 0.70 kg
Wood	90.7%	88.0%	Particle board	Plywood	1 m^3 : 0.6 m^3
Glass	94.7%	60.5%	Glass cullet	Packaging glass	1 kg : 1 kg
CDW - HQ[1]	NP	99.4%	Recycled aggregate - HQ[1]	Natural aggregates	1 kg : 1 kg[4]
CDW - LQ[2]	99.5%	99.4%	Recycled aggregate – LQ[2]	Natural soil	1 kg : 0.65 kg (sub-base) 1 kg : 0.58 kg (fillings)

NP = Not Performed step

[1] CDW with very low impurities originating from selective demolition; High Quality (HQ) recycled aggregates can be produced and used in high-grade applications

[2] CDW with high impurities originating from traditional demolition; Low Quality (LQ) recycled aggregates are produced and used in low-grade applications

[3] The recycling process of aluminium scraps was not included in the system boundaries as the aluminium scraps, at the inlet of the furnace for the production of secondary aluminium, were assumed to substitute the unalloyed Al99.7 at the inlet of the alloying process

[3] It is 1 kg : 0.67 kg in the case study, where the real situation of Lombardy region (i.e. market for recycled aggregates not completely developed) is modelled (Borghi et al., 2018)

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Table 3. Environmental and energetic performance associated with the selective demolition scenario, in case of High Quality (HQ) and Low Quality (LQ) recycled aggregates from CDW, in comparison with the traditional demolition scenario.

Impact category or Indicator	Unit	Traditional demolition	Selective demolition_HQ[1]	Selective demolition_LQ
Climate change	kg CO_2 eq	6.71	3.50	6.24
Ozone depletion	kg CFC-11 eq	1.19E-05	1.18E-05	1.22E-05
Human toxicity, non-cancer effects	CTUh	1.13E-05	1.94E-05	1.99E-05
Human toxicity, cancer effects	CTUh	1.50E-04	1.64E-04	1.64E-04
Particulate matter	kg PM2.5 eq	4.36E-02	4.41E-02	4.60E-02
Photochemical ozone formation	kg NMVOC eq	0.375	0.381	0.397
Acidification	molc H+ eq	0.440	0.632	0.651
Terrestrial eutrophication	molc N eq	1.50	1.47	1.54
Freshwater eutrophication	kg P eq	-6.76E-02	-7.80E-02	-7.77E-02
Marine eutrophication	kg N eq	0.130	0.152	0.158
Freshwater ecotoxicity	CTUe	4349.5	5100.6	5112.2
Water resource depletion	m3 water eq	0.716	0.782	0.791
Mineral & fossil resources deplet.	kg Sb eq	-5.94E-05	-7.18E-05	-3.58E-06
CED	MJ	303.3	109.2	155.4
Mineral Resource indicator (Sand and Gravel)	kg	-1198.6	-1545.7	-1172.8
Mineral Resource indicator (Gypsum)	kg	-0.112	-0.127	-0.126

[1] Replacement factor equal to 1 kg RA : 0.67 kg NA

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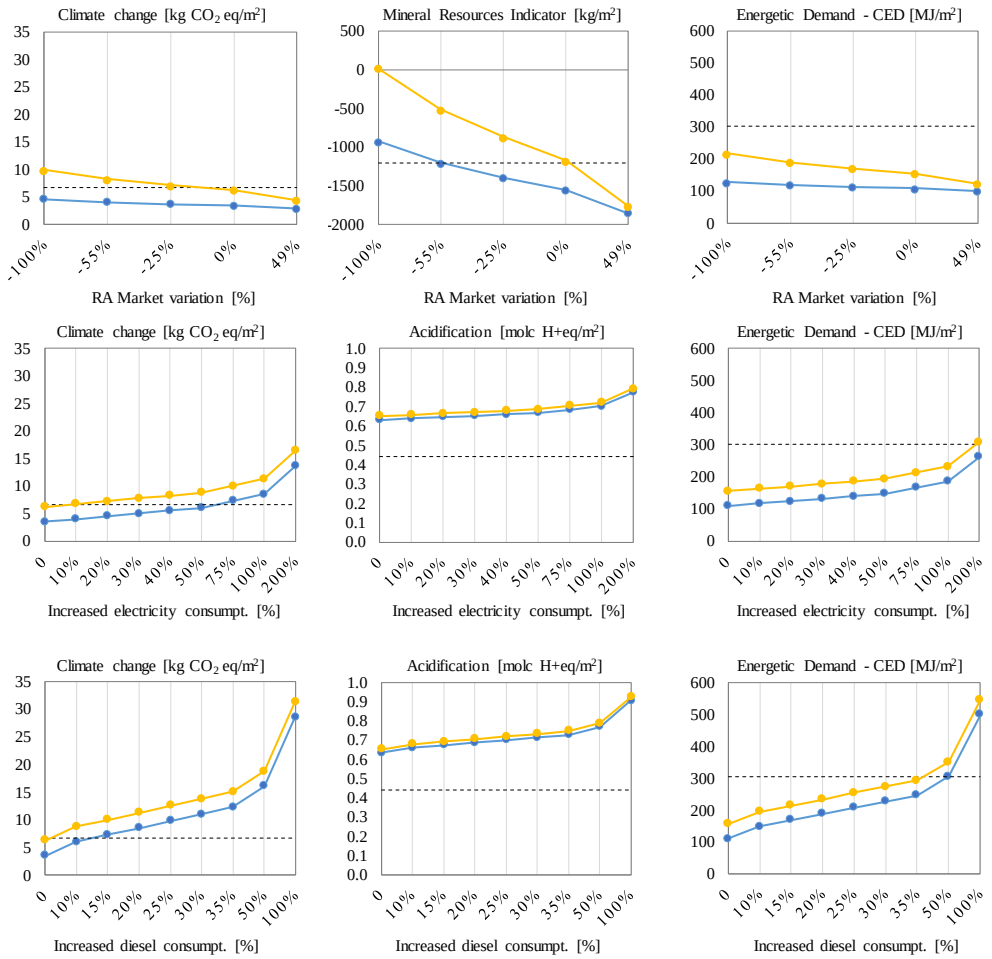
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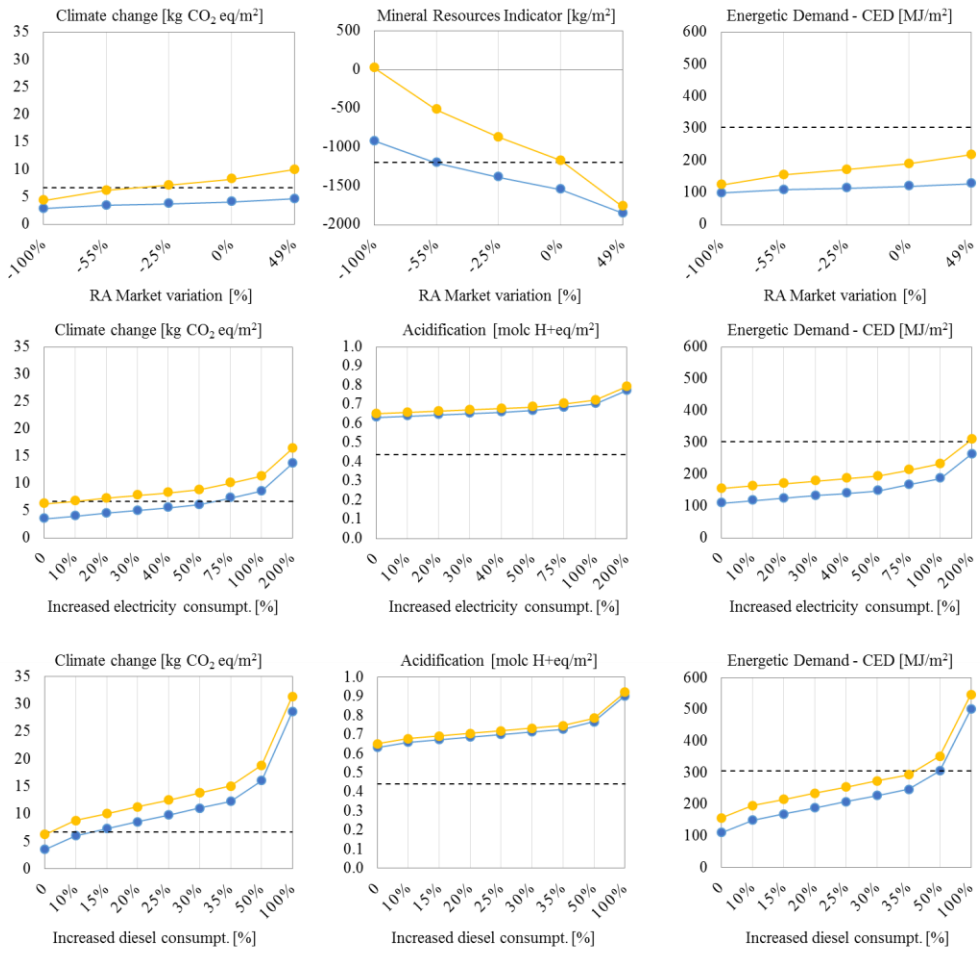

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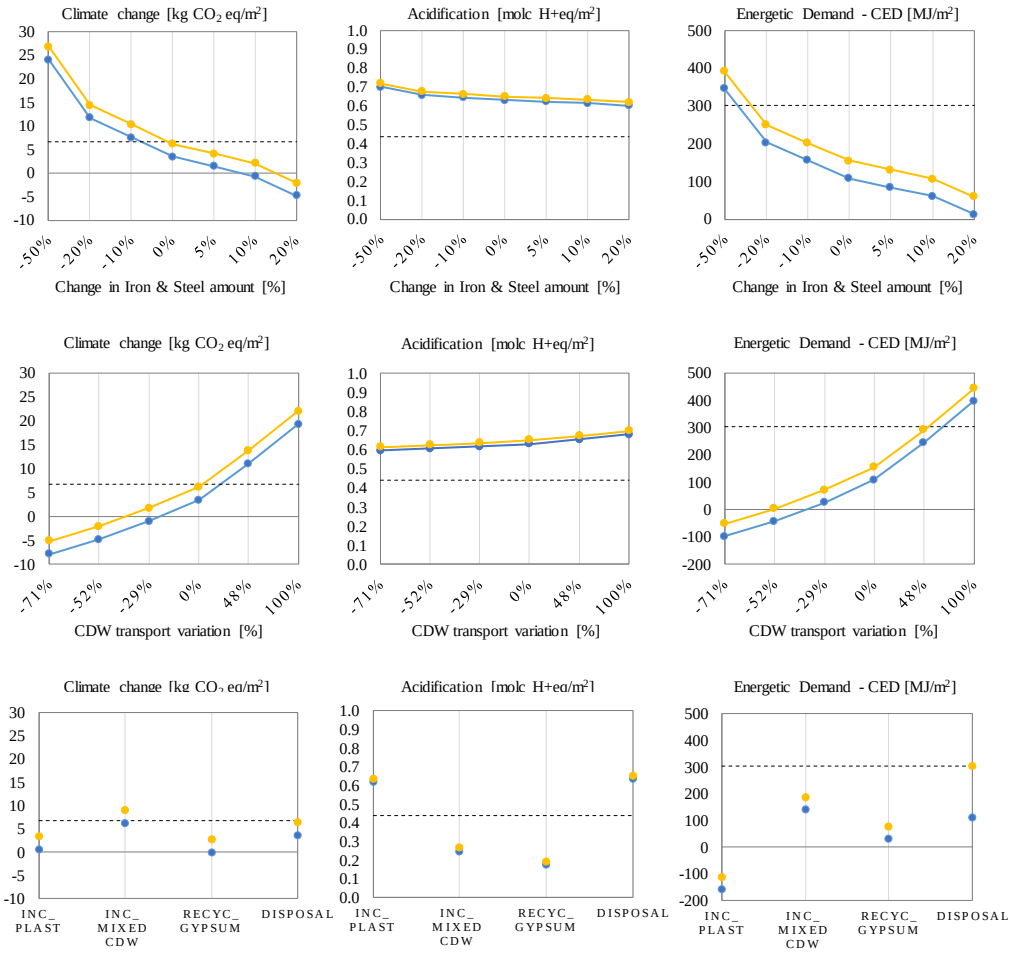
Climate change [kg CO2 eq/m2]
Acidification [molc H+eq/m2]
Energetic Demand - CED [MJ/m2]
Change in Iron & Steel amount [%]
CDW transport variation [%]
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INC_ MIXED CDW
RECYC_ GYPSUM
DISPOSAL
Selective_Dem_HQ
Selective_Dem_LQ
Traditional demolition

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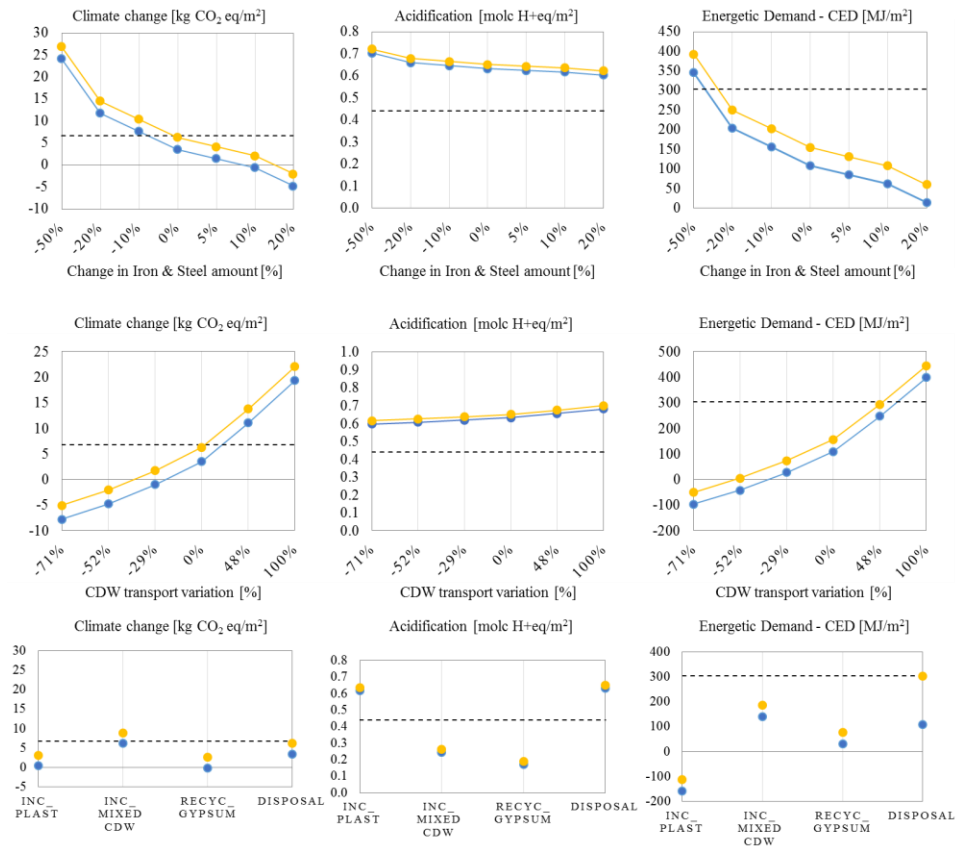

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***Declaration of Interest Statement**

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: