Circular Management of Tunnel Excavation Materials in Transport Infrastructures: An LCA Approach

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Abstract. The construction of a transport infrastructure has significant environmental impacts in terms of overall emissions and resource consumption, making the transition to circular models a priority. This study examines the management of excavated materials (ESR) generated by the Terzo Valico dei Giovi railway project (Italy), assessing their reuse for the renaturalisation of disused quarries.

The analysis, based on the Life Cycle Assessment (LCA) methodology, identifies three indicators – Climate Change, Land Use and Abiotic Resource Depletion–Fossil – to compare traditional and mechanised excavation methods to identify the specific impacts of ESR management.

The results show that mechanised excavation has a greater impact on Climate Change, mainly due to the logistical complexity involved in the proper management of ESR. Overall, their reuse for the morphological restoration of quarries generates benefits in terms of Land Use, contributing to landscape continuity. On the whole, the study highlights how the circular management of ESR represents a key element for the sustainability of major infrastructure projects, transforming excavated materials into resources that benefit the local area.

Keywords: LCA · Excavated Waste · Circular Economy · Railway Infrastructures · Post-extraction Land Rehabilitation

1 Introduction

European plans for the renovation and upgrading of infrastructure assets also involve substantial investments in the construction of new strategic projects for the transport of people and goods [1]. As supported by the Trans-European Transport Network (TEN-T) policy, this means developing an integrated, sustainable and efficient European transport network in line with the sustainability objectives set for 2050 [2].

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To achieve these goals and build a connected community network, new infrastructure arcs need to be built where they are lacking. However, as highlighted in the literature, the construction sector continues to be a critical in terms of the transition to decarbonisation and resilience objectives [3]. Furthermore, this sector is responsible for over a third of global emissions in terms of CO2 and resource consumption [4].

Part of these impacts can be attributed to the consumption of non-renewable resources necessary for the construction of infrastructure, mainly in terms of land use [5]. Land use is defined as: physical occupation of land [6, 7] and the sourcing and use of soil and its derivatives as construction materials. This condition makes the construction sector one of the most suitable for a transition to a circular economy [8], as approximately one third of the total waste produced in the European Union consists of construction and demolition (C&D) waste, with a reuse rate of less than 50% [3].

Consequently, the issue of resource efficiency, including reuse purposes, is rapidly gaining interest, but the response remains vague, as the current regulatory framework leaves it up to construction companies to assess the use of the material they produce during excavation operations, resulting in a complex management process [9]. Therefore, the construction of new infrastructure, especially when it involves underground sections, constitutes an essential part of total C&D waste, but is rarely treated or described in an independent framework [10].

The literature highlights a gap in the reuse of excavated soil and rock (ESR) from underground construction projects [11] and, as also noted in Italian regulations, its treatment depends on whether it is classified as a byproduct or waste based on its chemical composition or environmental compatibility with final disposal sites [9]. Furthermore, its management and the capitalisation of the impacts generated are delegated to the builder and other stakeholders in the construction chain with whom it interfaces – subcontractors, transporters and owners of the destination sites.

As evidenced by literature and key operational experience, ESR are deposited in abandoned quarries in the area to restore their original morphology for the purpose of renaturalising the area or providing the territory with new agricultural production facilities [12, 13]. This activity is part of the construction site operations that are regulated and controlled on the basis of the Soil Use Plan - *Piano di Utilizzo* (PdU) that the builder is required to draw up, summarising the entire logistics chain and assessment of the quantities of ESR produced and the sites identified for its disposal [9].

This article aims to focus attention on the circular use of resources during the construction process, going beyond the standard view of the construction sector, which applies the principles of the circular economy to properties as a source from which to draw new resources during demolition [11, 14]. For large-scale linear infrastructure, managing on-site materials offers significant economic benefits for supply chain stakeholders and environmental advantages through their reuse or disposal.

However, the excavation techniques adopted for infrastructure construction entail different management approaches for ESR. Two main methods are distinguished: traditional excavation and mechanized excavation, which—regarding the classification of ESR as a by-product—require different treatments. Material excavated by traditional methods (i.e., explosives and equipment such as backhoes, excavators, and bulldozers) is classified on site and transferred directly to the final disposal facility defined in the

PdU. Mechanized excavation uses a Tunnel Boring Machine (TBM), which employs conditioning additives to facilitate advance. As a result, the excavated material is chemically altered and must undergo an intermediate storage phase at a designated facility to allow evapotranspiration of these additives before final disposal [15, 16].

This management approach extends the value chain of sustainable infrastructure by assigning additional costs to the construction phase to ensure project sustainability. This bias can be mitigated through the application and modelling of measurement tools and methodologies capable of quantifying the effects of sustainable solutions from the construction stage onward. Life Cycle Assessment (LCA) models are being developed to address this structural gap in the infrastructure construction sector [14, 17, 18]. Although LCA is recognised for assessing the benefits of responsible construction material use, its application to evaluate impacts from materials generated during infrastructure construction—i.e., ESR—remains limited.

Building on these points, this study addresses the following research questions.

RQ1: What are the environmental costs of reusing ESR for the renaturalisation of quarries? Are these costs balanced by the benefits produced by this action?

RQ2: To what extent do the technologies employed in infrastructure construction influence the environmental impacts associated with the proper management of ESR?

RQ3: In what terms is it possible to quantify the commitment to the management of ESR and its effects?

2 Case Study

This section examines Terzo Valico dei Giovi (TV), a new railway link of the TEN-T Rhine–Alps corridor currently in its final construction stages. As the project is largely underground, the management of excavated materials is a key issue. Particular attention is given to excavation methods and their role in identifying strategies for reusing extracted materials as by-products.

The case study was selected because of the infrastructure's strategic relevance and the large volumes of material generated during construction. In addition, publicly available documentation and data from Italian *Ministero dei Trasporti* and *Ministero dell'Ambiente e della Sicurezza Energetica*, enable detailed modelling of extraction, transport and disposal processes.

2.1 Terzo Valico Dei Giovi, Italy

TV railway project is a major infrastructure currently under construction (2012-on going) in Northern Italy connecting the port of Genoa with the Po Valley. The new line extends for approximately 53 km, largely developed underground through a complex tunnel system crossing the Ligurian Apennines between Liguria and Piedmont and the use of twin-bore tunnels results in nearly 90 km of total tunnelling, generating large volumes of excavated rock and soil. Excavation is carried out using both conventional methods: traditional and usage of TBM.

From an organisational perspective, construction activities are divided into six construction lots and distributed across 15 main operational construction sites along the

alignment, supported by 6 base camps and additional service facilities: such as quarries or deposit sites. This articulated construction system reflects the territorial scale of the project and the logistical complexity associated with underground infrastructure works.

The tunnelling activities produce approximately 15 million m3 of ESR. Rather than being entirely disposed of as waste, a significant share is managed within circular reuse strategies, including environmental restoration interventions such as the renaturalisation of exhausted quarry sites. In this framework, excavation material management represents a key factor in assessing the environmental performance of the project during the construction phase.

2.2 Management of Excavated Soil and Rock

This section analyses the ESR management system implemented during the construction of the TV, with particular focus on the Piedmont section, which provides a more comprehensive view of the material reuse cycle. To this end, the TV's PdU is reviewed and supplemented with the EMAS Environmental Statement, which is used to provide additional data and identify the main strategies adopted in ESR management [19–21].

In Piedmont, 9.4 million m3 of ESR are generated by 11 active construction sites employing both excavation methods. Of this volume, 22% are reused on site for other construction activities, while the remaining 78%constitutes surplus material requiring classification. Over the past five years, approximately 10% of this portion has been classified as waste and disposed of [19, 21]. The remainder has been transferred to a network of designated storage facilities located across Liguria and Piedmont.

ESR destination sites are identified within the PdU based on several criteria, including distance from active construction sites, storage capacity and type of material accepted, site condition, and potential future land use. In Piedmont, these sites are classified as hillside quarries when located in mountainous areas or as lowland quarries in flat terrain. Only inactive quarries are selected, as material deposition enables morphological recontouring for renaturalisation or the restoration of agricultural land continuity. Through this process, 37 quarries have been identified as capable of accommodating the entire volume of material excavated from the TV; transport plans further define mandatory road routes from the construction sites to the final destinations [22].

Mechanized excavation, however, requires a different ESR management approach. Additives used for TBM operation may compromise the environmental compatibility of the material with the destination sites. For this reason, the PdU includes an intermediate storage facility, DP22 – Cascina Romanellotta (DP22), intended for the temporary stockpiling of material in low-height heaps over a large surface area to promote the evaporation of conditioning agents and restore suitability for reuse.

To ground the LCA modelling in a real-world case study, this article focuses on the DP07 – Cascina Bolla quarry (Alessandria, Italy). The project aims to restore the site's original morphology to ensure continuity with the surrounding agricultural landscape. DP07 was selected primarily due to its advanced ESR deposition stage. The site treats materials from four construction areas: COP5 and COP11 (traditional excavation) and COP7 and COP20 (TBM). As shown in Fig. 1, TBM materials are first stockpiled at DP22 before being transported to DP07 or, if unsuitable, sent to landfill.

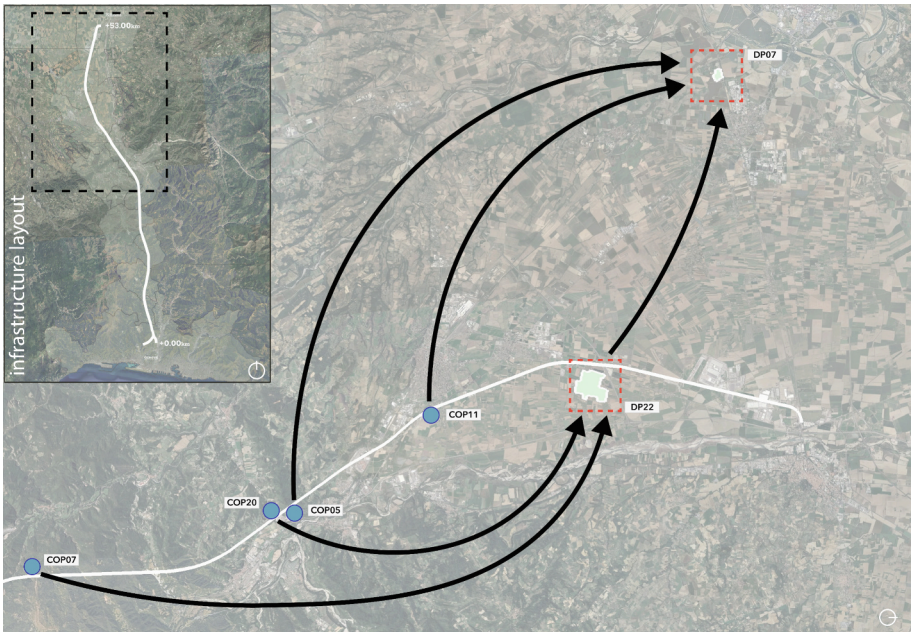


Fig. 1. Planimetric overview of the ESR management process from the operational construction sites to DP22 and DP07, including the corresponding transport routes. The upper-left inset shows a schematic representation of the TV project with the study area highlighted.

3 Methodology

3.1 The LCA Methodology

The analysis has been performed adopting the LCA methodology, consistently with international standards [23, 24] that define it as the *compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*. According to the standards, the analysis is articulated into four main steps: *Goal definition*, *Scope definition*, *Inventory analysis* (LCI) and *Impact assessment* (LCIA). Moreover, *Interpretation* of interim and final results throughout the methodology is required to refine the analysis, given the iterative nature of LCA.

The current standard for the Sustainability Assessment of Civil Engineering Works, EN 17472:2022 [25], divides the life cycle of a civil engineering work into modules grouped into three main categories: Category A (A1–A5) covers pre-construction, product, and construction process stages; Category B (B1–B8) addresses the use stage; and Category C (C1–C4) encompasses end-of-life management stages.

As the material which is the core of the present study is the waste generated during the excavation activity performed as part of the realisation process of a railway infrastructure, the analysis here reported is meant to be interpreted as a focus on the module A5 described by the above mentioned standard (A5 – Construction and Installation processes). In fact, the standard specifies that the waste-management processes for all waste materials generated on the construction site shall be included within the boundaries of Module A5.

3.2 Goal Definition

The objective of the analysis was to estimate the potential environmental impacts associated with the waste management system of the material generated by tunnel excavation, representing a real-world construction scenario. Thus, the TV project was reviewed and it was decided to focus on the waste management chain in Piedmont.

The system under investigation manages waste produced by both conventional and mechanized tunnelling methods and considers the possibility that the material may be used for the recultivation of a decommissioned limestone quarry. Given this context, the research group initially sought to adopt a material-specific perspective, separately assessing the impacts arising from the activities inherent to the processing required for each type of waste. Accordingly, the analysis was initially intended to highlight the effects of the excavation technique on the overall impacts, as well as the role of the material environmental compatibility, which is expressed by the fraction of waste destined for landfill.

Subsequently, the aim was to adopt the perspective of the real-world waste managing system (system-level perspective), taking into account the actual origin and proportions of the treated waste materials. Considering environmental aspects of common concern, the impact evaluation focused on quantifying the potential effects on climate, resulting from greenhouse gas (GHG) emissions; the potential impacts derived from the exploitation of the land resource; and the consumption of energy fossil sources.

3.3 Scope Definition

System Description. From a material-specific perspective, the analysed waste management chain begins when excavated material from either traditional or mechanised tunnelling reaches the construction site gate after removal from the excavation face. At this stage, the fraction suitable for internal recycling as a substitute for virgin aggregates (VA) in earthworks (*IR*) is separated based on its mechanical properties, while the remaining waste follows different pathways depending on the excavation method.

Two main material flows are identified: from traditional tunnelling (material type M-A) and from mechanized tunnelling (material type M-B). While M-A is directly transported to destination, M-B requires an intermediate storage stage at a Temporary Deposit (TD) for additive evapotranspiration. M-A is characterised based on its environmental compatibility and divided into a fraction that can be effectively used for limestone quarry recultivation and a fraction destined for landfill disposal (*W*).

After evapotranspiration, the M-B material is separated into the *ER* and *W* fractions and subsequently hauled to the final disposal.

From a system-level perspective, the waste chains are integrated into a broader waste management framework involving two mechanized tunnelling sites (COP20 and COP7) and two traditional tunnelling sites (COP5 and COP11). The recyclable fraction is directed to the recultivation of the DP07 quarry and M-B material is first transported to the DP22 temporary deposit.

Declared Unit. When a material-specific perspective is adopted, the analysis is conducted with reference to 1 t of excavated material that has been transported to the construction-site gate and it is ready to be processed according to its origin. Subsequently,

when a system-level perspective is adopted, the declared unit is identified with 1 t of material that has reached the decommissioned quarry for recultivation.

System Boundaries. The potential environmental impacts addressed by the present study are part of those that can be assigned to Module A5 (Construction and Installation processes), as described by the standard EN 17472:2022. More specifically, only a subset of Module A5 is here analyzed; in fact, the activities that fall within the boundaries of the investigated system are exclusively those related to waste management. Consequently, impacts associated with the excavation activity itself are not of interest in the framework of the present analysis. For clarity reasons, this subset will be here named Module A5 – Waste management Fig. 2.

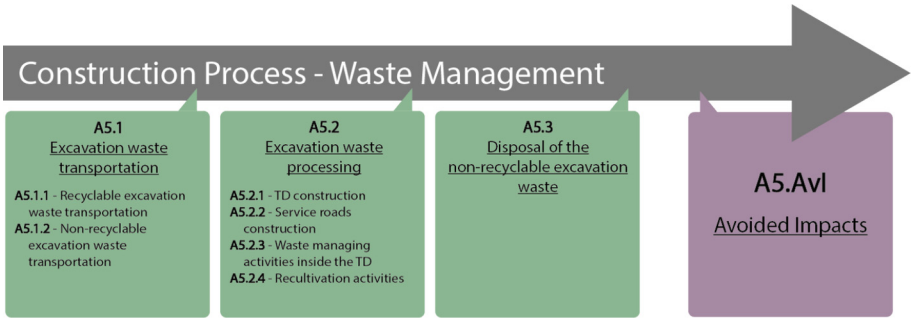


Fig. 2. Flowchart of the waste management subset of Module A5 of EN 17472:2022 to define avoided impacts and the system boundaries of the methodology.

As illustrated in Fig. 2, Module A5 is divided into three main submodules: excavation waste transportation (A5.1), excavation waste processing (A5.2), and disposal of non-recyclable excavation waste (A5.3). A5.1 includes the transport of both recyclable material to the temporary deposit or decommissioned quarry and non-recyclable material to landfill. A5.2 covers the main processing activities within the temporary deposit, including infrastructure works, internal handling operations, and recultivation activities. Finally, A5.3 refers to the landfill disposal of the non-recyclable fraction.

The internal use of excavated waste in substitution of VA may be considered in terms of avoided production of primary materials, which results in a negative impact. For this reason, an additional sub-module was introduced (AvI – Avoided Impacts).

To keep the results as general as possible, transportation-related impacts were excluded when adopting a material-specific perspective.

LCIA Methodology. In accordance with the objectives defined in the Goal Definition, the Life Cycle Impact Assessment (LCIA) methodology adopted in the present study is the one prescribed by the EN 15804 standard [26], as implemented in SimaPro v.10.2.0.2. This methodology encompasses a total of 16 impact categories and specifically addresses those relevant to the objectives of the study: Climate Change – Total (CC-Total), Abiotic

Depletion of Resources – Fossil fuels (AD-Fossil), and Land Use (LU). The impact category indicators, their unit of measurement, and the respective models used for impact quantification are shown in Table 1.

Table 1. Details of the adopted LCIA methodology.

Impact category	Indicator	Unit	Model
CC-Total	Global Warming Potential (GWP-total)	Kg CO_2 eq	Baseline model of 100 years of the IPCC based on IPCC 2013
AD-Fossil	AD Potential for fossil resources (ADP-fossil)	MJ	CML 2002, Guinée et al., 2002, and van Oers et al. 2002
LU	Potential Soil quality index (SQP)	Pt	Soil quality index based on LANCA

Working Hypothesis. This study relied on several working assumptions due to the lack of primary data. For transparency, the main hypotheses are summarised below.

From the technical documentation available on the website of the italian *Ministero dell'Ambiente e della Sicurezza Energetica* [19, 20], it is known that the overall quantity of excavated material originating from construction yards placed in Piedmont region is approximately equal to 9.4E + 06 m^3. It is also known that around 2.1E + 06 m^3 on average are immediately recycled inside the construction sites in substitution of VA. However, no site-specific data is publicly accessible to our best knowledge. For this reason, it is assumed a constant rate of internal recycling equal to $IR = 22\%$, , derived from the available averages. Regarding the remaining part (78%), it is known that between 0% and 12% of the material is not suitable for limestone quarry recultivation and it is then destined to landfill. For this reason, the waste rate W is made variable and it ranges from 0% to 12% (scenarios W0 and W12). For completeness, it is also considered the hypothetical scenario were the whole mass of excavated material (apart from the fraction internally recycled) is destined to landfilling (scenario W78).

As no site-specific data is available about the quantity of material exiting from each construction site, it is assumed that the overall value is equally distributed among the sites located in Piedmont region (about 6.7E + 05 m^3 each, after internal recycling). Considering that the whole mass of excavated waste originated from the four analysed construction yards is entirely disposed either in a landfill (according to W) or at the decommissioned quarry ($ER = 100 - IR - W$), the origin of the material being delivered to the quarry is homogeneously distributed.

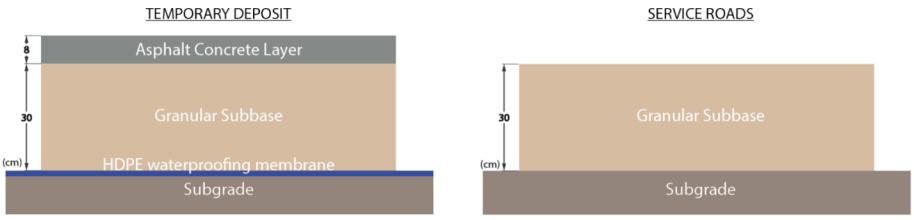


Fig. 3. Stratigraphic layout of the Temporary Deposit and the Service Roads, showing the layer thicknesses and the constituent materials as specified in the design sections.

Accessory facilities include the temporary deposit (1.68E + 05 m2) and service roads (1.85E + 04 m2), both built at the start of excavation. For each one, an operative life of 14 years and full end-of-life recycling were assumed. Structural details for the TD and service roads follow standard construction practices and the stratigraphy shown in Fig. 3. The asphalt mix was hypothesised to be a conventional hot mix asphalt, commonly adopted in binder courses (bitumen content, p_b, of 4.5% with respect to the aggregates weight, in situ density, MV_{AM}, of 2.3 t/m^3), whereas the in situ density of the subbase was set at 1.9 t/m^3.

The relative positions of the construction sites, the decommissioned quarry and the temporary deposit are known and are reported in Table 2. A transportation distance within the temporary deposit of 1.6 km is accounted for. Additionally, other distances have been assumed. External transport distances are set and supposed as follows: 100 km to the landfill from both construction sites and the TD; 15 km from the aggregate quarry to the TD; and 35 km from the quarry to the asphalt plant. Additionally, the asphalt plant and the waterproofing membrane retailer are located 20 km and 50 km from the TD, respectively.

Table 2. Excavated material transportation distances.

Origin	Distance to D22 (km)	Distance to quarry (km)	Total (km)
COP5 (traditional)	-	33.4	33.4
COP11 (traditional)	-	28.1	28.1
COP20 (mechanized)	18.05	21.8	43.0*
COP7 (mechanized)	7.35	21.8	32.3*

* the distance comprises the hauling activity which is carried out inside the TD.

Finally, the hourly productivity of the equipment used within the system boundaries was assumed and is reported in Table 3.

Table 3. Equipment hourly production.

Equipment	Hourly production (-)
Roller (for subgrade compaction)	380 m^3/h
Roller (for subbase compaction)	200 m^3/h
Roller (for asphalt course compaction)	60 m^3/h
Grader (for subbase formation)	3780 m^2/h
Paver (for asphalt course formation)	220 t/h

Allocation. The impacts of the construction and the demolition activities, at the end of the excavation process, of the temporary deposit and the service roads need to be allocated to 1 t of waste material which is transported to the deposit and stored. Regarding the total volume of M-B exiting from the gates of the construction sites (i.e., 1.3E + 06 m^3), an average volumetric mass can be set at 1.7 t/m^3, resulting in an overall transported mass of 2.28E + 06 t. Then, the allocation factor (A):

$$A = \frac{1}{M_{TD}} = \frac{1}{M_{tot} \cdot Ex} = 4.4E - 07 \quad (1)$$

where M_{TD} is the total mass of excavated waste which is stored in D22 and M_{tot} is equal to the overall mass which is excavated in the construction sites.

3.4 Inventory Analysis

The inventory analysis involves the collection of data which is required to model the system under investigation. Since no primary data about the elementary flows exchanged with the Ecosphere by the unit processes involved was collected during this research activity, all the unit processes were modelled according to data available in Ecoinvent v3.11 database [27]. A comprehensive list of the selected items and datasets for each sub-module is provided in the Appendix section. (Tables 6, 7, 8, 9 and 10).

4 Results and Discussion

This section presents and discusses the results of the LCIA conducted on the management of ESR. To ensure a clear reading of the following sections and to clarify the technical terminology, acronyms, and scenario parameters adopted, Table 4 provides a summary glossary for reference.

Table 4. Summary glossary of technical terminology and scenario parameters adopted.

Category	Term	Description
Materials	M-A	Material from traditional excavation
	M-B	Material from mechanised excavation
Waste Scenarios	W0, W12, W78	Waste rates: percentage of material deemed unsuitable for recovery (0%, 12%, and 78%)
	IR	Internal Recycling ESR, fixed rate (22%)
LCA indicators	CC-Total	Total greenhouse gas emissions
	LU	Impact on land use resources
	AD-Fossil	Consumption of fossil energy resources
Waste Management	A5.1.1/A5.1.2	Impacts related to the transportation of ESR
	A5.2.1/A5.2.2	Impacts from the construction and demolition of the TD and internal service roads
	A5.2.4	Recultivation activities for quarry restoration
	A5.3	Landfill activities impacts

4.1 Material-Specific Perspective

Accordingly to the goals, first, the quantification of the impact indicators is performed adopting a material-specific perspective. Hence, the results are computed considering 1 t of material to be processed according to its origin (M-A or M-B). No impacts from transportation were considered at this stage of the analysis. As mentioned before, three scenarios of waste rate have been considered, to assess the influence of the environmental compatibility of the material on the impacts of the waste management chain. In the following Table 5 the results are reported.

Table 5. Impact scores from LCIA for 1 t of waste material (A&B).

Material	W0	W12	W78	Avoided impacts
Climate Change – total (CC-total) (kgCO2eq/t)				
M-A	1.68E-02	1.09E + 00	7.17E + 00	–8.01E-01
M-B	2.31E + 00	3.38E + 00	9.46E + 00	–8.01E-01
Land Use (LU) impact category (Pt/t)				
M-A	–1.01E + 02	–1.54E + 01	4.69E + 02	–2.36E + 01
M-B	3.54E + 02	4.39E + 02	9.24E + 02	–2.36E + 01
Depletion of Abiotic Resources – Fossil fuels (AD-fossil) (MJ/t)				
M-A	2.19E-01	1.80E + 01	1.19E + 02	–1.17E + 01
M-B	5.24E + 01	7.02E + 01	1.71E + 02	–1.17E + 01

The figures in columns W0 to W78 represent the impacts associated with the waste management chain, while the column Avoided impacts describes the effect of recycling a portion of the waste (*IR*) as a substitute for VA. The negative values in the last column result from the comparison between a hypothetical scenario (where the same quantity of material originates from a quarry) and the current alternative. Due to the omission of transportation, the processing of M-A includes only recultivation and landfilling, whereas processing M-B also comprises the construction and demolition of the temporary deposit (allocated) and the placement of material within it.

Limiting the analysis to the largest observed waste rate scenario (W12) and considering the contribution of individual activities to the overall impact, the recultivation process accounts for 1.2% of the total Global Warming Potential and 1.0% of the Abiotic Depletion Potential of fossil resources for material M-A. These results highlight the dominant influence of the landfilling activity on the total impact score. This outcome is not unexpected, as the literature consistently attributes a significant environmental burden to the landfilling of civil works and construction wastes [13, 18, 28]. With regard to the Land Use impact category, recultivation generates a negative impact because land previously allocated to quarrying is restored to an uncontaminated condition. This outcome is in line with the current research on the topic [29]. The positive effect of recultivation on this impact category is visible in scenarios W0 and W12, where the environmental gain is not yet completely counterbalanced by the impact deriving from landfilling. This effect is gradually lost at higher waste rate values.

For M-B (W12), the most impactful activity for Climate Change is the construction and demolition of the temporary deposit (allocated), accounting for approximately 59% of the total impact, followed by the landfilling of the non-recyclable fraction (32%) and the placement of material within the temporary deposit (8%). This trend is consistent with the results of the Depletion of Abiotic Resources – Fossil fuels impact category. For Land Use, however, the construction and demolition of the internal service roads become the third most impactful activity.

Analysis of the results reported in column W12 demonstrates a clear influence of the material's origin on the impacts associated with the waste-management chain. The increase induced by the activities associated with waste material originating from mechanized tunneling reaches 310% for Climate Change and 390% for the Abiotic Depletion of Resources. The influence of the material's origin becomes even more pronounced when examining the Land Use impact indicator. In this case, the benefit (expressed as a negative impact value) associated with quarry re-naturalization is completely offset by the impact generated by the construction and demolition of the temporary storage area and the service roads within the construction site.

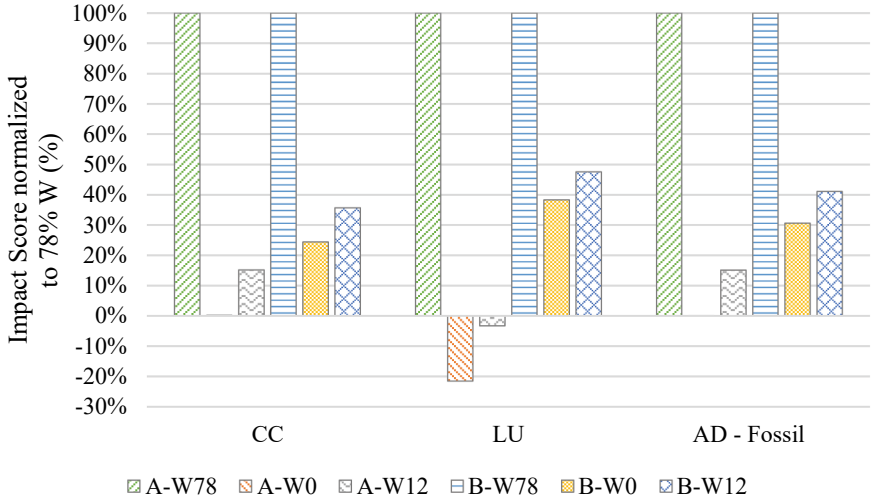


Fig. 4. Environmental impact of 1 t of excavated materials A and B, by origin and waste ratio.

In Fig. 4 the impact scores (excluding the benefits deriving from avoided impacts) for the two analyzed material (M-A and M-B) are shown, each normalized to the most impactful waste rate scenario (W78). In this graphical representation, W78 is always assigned 100% of the impact score. The bar graph effectively illustrates the influence of the environmental compatibility on the impact results; for instance, for material M-A, a reduction of the waste rate from 78% to 12% leads to an approximately 85% decrease in both CC-Total and AD-Fossil, while the LU category indicator shows negative values of impact. A smaller reduction is observed in case of M-B, due to the non-negligible impacts associated with the construction and the demolition of the temporary deposit and service roads. In this case, the mitigation ranges from roughly 50% (LU) to about 65% for the Climate Change category.

4.2 System-Level Perspective

The results obtained for individual materials are used to compute the overall impact for 1 t of material disposed at DP07, assuming that the waste originates from 4 distinct construction sites (COP5, COP11, COP20, COP7), located in the vicinity of the decommissioned quarry. The origin of the waste is evenly distributed among the sites (25% each). Figure 5 reports the results of W12, disaggregated by sub-submodule and normalized with respect to the total impact score.

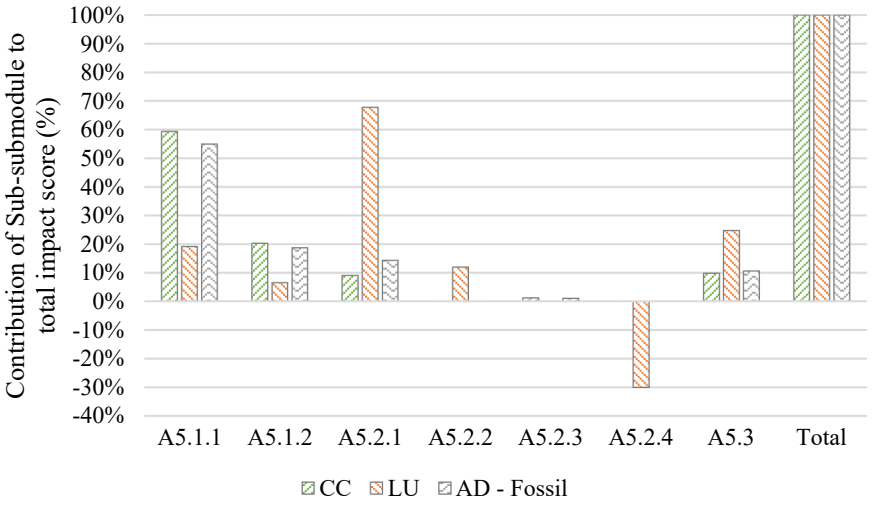


Fig. 5. Environmental impacts of 1t of material disposed at DP07 (excluding avoided impacts).

Overall, the potential contribution of 1 t of material to Climate Change is equal to 1.66E + 01 $kgCO_2eq$, while the potential benefit derived from the avoided products accounts for –1.21E + 00 $kgCO_2eq$. Regarding the Land Use, the total impact of Module A5 – Waste chain reaches 4.30E + 02 Pt, which incorporates the beneficial outcomes of recultivation (negative contribution), but does not include the avoided impacts from internal recycling (–3.56E + 01 Pt). Finally, the potential depletion of fossil resources reaches 2.54E + 02 MJ (–1.76E + 01 MJ).

The results presented in Fig. 5 allows the identification of the critical stages of the system for each impact category. For CC-Total and AD-Fossil, the largest contribution to the total impact originates from transportation of recyclable fraction of the excavation waste (A5.1.1), followed by the transportation of the non-recyclable portion (A5.1.2). Regarding the Land Use impact category, as predictable, the most impactful life-cycle stage is the construction and demolition of the temporary deposit (A5.2.1), followed by the transportation of the recyclable waste (A5.1.1) and the construction and demolition of service roads (A5.2.2). The positive contribution of the recultivation activity (A5.2.4) is represented by the negative bar and reflects the restoration of the original landscape.

5 Conclusions

In the present research activity, the impacts of different waste-management chains resulting from distinct excavation techniques were investigated. Specifically, ESR from traditional excavation technique and mechanised approaches were compared in terms of Climate Change, Land Use and Abiotic Resource Depletion – Fossil adopting a LCA methodology.

This activity has proved that the use of ESR for the renaturalisation of decommissioned quarries has positive effects on the Land Use impact category, resulting in a reduction of the impact score. Anyway, this activity has a cost in terms of Climate

Change and Abiotic Depletion – Fossil, although almost negligible if compared to the one related to transportation.

Moreover, although mechanised excavation techniques allow for faster construction timelines, the management of ESR involves a more complex logistic system, requiring the construction of temporary storage areas and service roads, ultimately leading to a higher impact value per ton of input waste.

Although the LCA model presented in this paper was developed on a specific case study, it provides a useful reference for developing site-specific models to assess the potential impacts of ESR in other contexts. Therefore, the results of this research may help raise awareness among general contractors of the benefits of excavation-waste management models, promoting circular resource-management practices such as the renaturalisation of decommissioned quarries.

Indeed, this study demonstrates how the adoption of a circular approach in the construction of transport infrastructure can offer significant opportunities for the development of sustainable solutions. However, it should be emphasised that the present analysis is based on several methodological assumptions made necessary by limited data availability and the strong site-specific nature of the case study, such as: a fixed internal recycling rate, a uniform distribution of ESR among the different production sites, and the estimation of transport distances. These assumptions inevitably introduce margins of uncertainty, which could be reduced through multi-scenario assessments and further research developments, both from a methodological perspective—through sensitivity and uncertainty analyses using Monte Carlo simulations—and by addressing existing data gaps through a multiple case-study approach that groups comparable ESR management scenarios by analogy.

In conclusion, this research has proved that adopting a circular approach in the construction of transport infrastructure offers an opportunity to develop sustainable solutions that contribute to the enhancement and value creation in the local environment.

Appendix

Table 6. Activities comprised in A5.1 sub-submodulus and adopted models.

A5.1 – Excavation Waste Transportation	
A5.1.1 – Recyclable excavation waste transportation	
M-A/M-B transportation from construction sites to decommissioned quarry (possibly via TD)	**(A)** Transport, freight, lorry, 16–32 metric ton, diesel, EURO 5 {RER}| market for transport, freight, lorry, 16–32 metric ton, diesel, EURO 5 | Cut-off, U
A5.1.2 – Non-recyclable excavation waste transportation	
M-A/M-B transportation from COP/TD to landfill	See **(A)**

Table 7. Activities comprised in A5.2 sub-submodulus and adopted models (part 1).

A5.2.1 – Infrastructure: temporary deposit	
A5.2.1.1 – Land transformation and occupation	
Transformation	Transformation, from annual crop, IT Transformation, to dump site, inert material landfill
Occupation	Occupation, dump site, inert material landfill
A5.2.1.2 – Raw materials extraction and processing for construction materials	
Production of virgin aggregates	**(B)** Gravel, crushed {CH}| gravel production, crushed | Cut-off, U
Transportation of virgin aggregates	See **(A)**
Production and transportation of bitumen	Bitumen adhesive compound, hot {GLO}| market for bitumen adhesive compound, hot | Cut-off, U
Raw materials extraction and transportation of the HDPE w.p.m	Adapted from EPD
A5.2.1.3 – Construction materials manufacturing	
Asphalt concrete production	Adapted from [30]
Manufacturing of the HDPE w.p.m	Adapted from EPD
A5.2.1.4 – Construction materials transportation	
Aggregates, asphalt concrete and HDPE w.p.m. transportation	See **(A)**
A5.2.1.5 – Construction activities	
Topsoil removal	Excavation, skid-steer loader {RER}| excavation, skid-steer loader | Cut-off, U
Subgrade compaction, laying and compaction of subbase and asphalt layer	**(C)** Machine operation, diesel, > = 74.57 kW, steady-state {GLO}| machine operation, diesel, > = 74.57 kW, steady-state | Cut-off, U
A5.2.1.6 – Demolition activities	
Demolition of the asphalt course	Adapted from [17]
Demolition of the subbase course	**(D)** Excavation, hydraulic digger {RER}| excavation, hydraulic digger | Cut-off, U
A5.2.1.7 – Landfilling of demolition waste	
HDPE w.p.m	Adapted from EPD

Table 8. Activities comprised in A5.2 sub-submodulus and adopted models (part 2).

A5.2.2 – Infrastructure: service roads	
A5.2.2.1 – Land transformation and occupation	
Transformation	Transformation, from annual crop, IT Transformation, to traffic area, road network
Occupation	Occupation, traffic area, road network
A5.2.2.2 – Raw materials extraction and processing for construction materials	
Production of virgin aggregates	See **(B)**
A5.2.2.4 – Construction materials transportation	
Aggregates transportation	See **(A)**
A5.2.2.5 – Construction activities	
Subgrade compaction, laying and compaction of subbase course	See **(C)**
A5.2.2.6 – Demolition activities	
Demolition of the subbase course	See **(D)**

Table 9. Activities comprised in A5.2 sub-submodulus and adopted models (part 3).

A5.2 – Excavation waste processing	
A5.2.3 – Waste managing activities inside the temporary deposit	
Laying of the excavated material	See **(D)**
A5.2.3 – Recultivation activities	
Limestone quarry recultivation	Recultivation, limestone mine - COPIA {CH}| recultivation, limestone mine | Cut-off, S

Table 10. Activities comprised in A5 modulus and adopted models.

Module A5 – Waste chain	
A5.3 – Disposal of the non-recyclable excavation waste	
M-A/M-B landfilling activity	Adapted from [31]
A5.B – Avoided products	
Avoided impacts from substitution of VA	See **(B)**

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