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The Impact of a Permeation Grouting Technique Quantitatively Assessed Through a Process-Focused Life Cycle Assessment

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***Abstract* – Permeation grouting treatments can be considered a well-established ground improvement strategy in urban built environments, where an accurate fine-tuning of its components can lead to tailored and efficient interventions. However, how to improve its overall environmental impact remains an open question. Using the Life Cycle Assessment (LCA) approach emphasizing the construction phase, this research highlights the leverages that can improve the environmental performance of this geotechnical construction process. The alternative approaches in terms of materials and processes are identified, quantified, and compared using the standard output of the LCA analysis and represent the ideal input for the three-phased sustainability assessment method for geotechnical infrastructure developed by the authors.**

***Keywords* – Built environment; eco-design; geotechnics; LCA; sustainability; transport infrastructure.**

1. INTRODUCTION

The construction sector needs to catch up on technological changes and on the ability to reduce its broad environmental impact. As a result, infrastructures and buildings are often considered a relevant part of sustainable development because of their crucial role in society, the economy, and the environment. This evidence is reflected in several studies highlighting trends and facts about the environmental concerns in the construction sector.

The construction industry is responsible for about 10 % of the global Gross Domestic Product (GDP), with 100 million people employed [1]. It consumes a large number of resources: 33 % of the global energy consumption and 40 % of the raw material consumption, contributing to 40 % of the global solid waste generation [2].

According to the study by Zamagni [3], the concrete production industry is responsible for about 7 % of global emissions, and the iron and steel industries come right after. For Benoît [1], material extraction and manufacturing account for about 90 % of the total environmental

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impact of a residential building, while resource extraction and manufacturing contribute about 60 % of the construction costs.

Right because construction products and processes, and particularly those involved in infrastructure creation, are essential components of the built environment, and even more because they also have a substantial environmental impact throughout their entire life cycle, there is a growing interest in those metrics and methods of their sustainability assessment with qualitative and quantitative approaches. This aspect is reflected in the paper of Pettinaroli and Susani [4], where the authors propose a three-phased assessment method combining a holistic sustainability indicator-based approach with an LCA construction process evaluation. Furthermore, the authors highlight the essential role of the LCA approach (both cradle-to-gate and cradle-to-grave) to fine-tune the sustainability of using specific construction materials, technologies, site management, waste management, reuse, and recycling during the whole life cycle of each investigated process. Thus, an optimization approach based on the single stage of the construction process provides the background for optimizing environmental performances based on tailored and customized sustainability needs and constraints.

This paper proposes a geotechnical ground improvement process as a case study describing the application of the proposed LCA-based approach in detail. The results of the analyses are presented and discussed. The background theoretical framework of this study is aligned with the method described in the study by Pettinaroli and Susani [4]. More specifically, an overall sustainable assessment is proposed by integrating the concept of the LCA to the EU Taxonomy regulation [5]. This is based on a list of six environmental objectives: of six environmental objectives: climate change mitigation and adaptation, sustainable use of water and marine resources, transition to circular economy, pollution prevention and monitoring, and preservation of biodiversity and ecosystems. The EU Taxonomy framework provides standards for measuring sustainability in the construction sector is provided by, a key requirement to access funding and financial leverage.

The EU Taxonomy is aligned with the Envision framework. This provides the guidance needed to initiate systemic change in the planning, design, and delivery of sustainable and resilient infrastructure, as the EU Green Deal requested. This framework includes 64 sustainability and resilience indicators, called "credits", organized around five categories [6]. The LCA would support better quantifying the sustainable criteria as proposed in the Envision framework.

Using LCA as a sustainability assessment tool, particularly its application to technological systems, is a consistent practice. Several studies [7]–[9] emphasize the need to look from a holistic approach when dealing with technological and supply chain systems. These studies reflect the need to address specific attention to energy efficiency and bio-based measures, strengthening the need for such measures as environmentally sustainable.

2. A METHOD IN THREE PHASES

As mentioned, this study wants to implement a three-step assessment method integrating LCA within the Envision and the EU Taxonomy framework. This pathway is essential in order to support engineering and designers in shaping sustainable choices and processes down to construction practices, particularly in the case of geotechnical engineers. Such an approach considers that:

– The current pressure that owners and investors are putting on the infrastructure construction industry to show substantial efforts toward sustainability;

– The complexity required to transparently and qualitatively comply with the EU Green Deal requirements (to get access to funding);
– The need for recognized third-party holistic criteria that can frame a project from the strategic level view down to the single construction process and, finally,
– The requirement to quantitatively demonstrate each sustainability choice/achievement scoring.

Specifically, the proposed method relies on full compliance with the EU Taxonomy, and the *do not significant harm* (DNSH) criteria [10], [11] supporting green financing for infrastructures [4].

The following figure represents a graphical synthesis of the proposed methodology based on a three-phase approach.

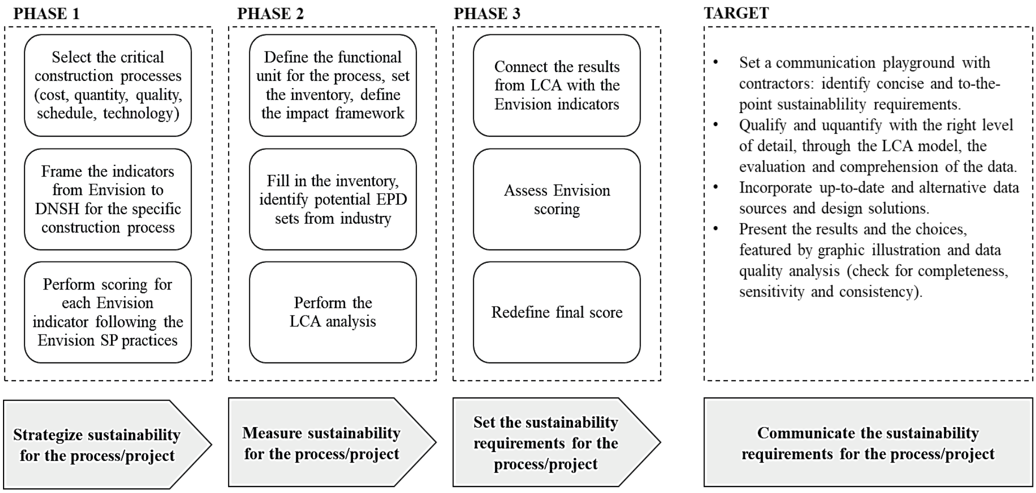

Fig. 1. The Three Phase Method [4].

The proposed approach will be applied to a specific case study within the field of geotechnical infrastructure, as described in the next section.

3. A Case Study for Ground Improvement Techniques

As a case study for applying the LCA methodology to the soil treatment systems exposed in the previous paragraphs, a hypothetical excavation site in Rozzano (Milan, Italy) was selected.

The choice of the location relied on the knowledge of the area deriving from previous experiences of the authors as designers, which provided the geological and hydrogeological information needed to complete the study.

The excavation site has a square shape with sides of 10 meters each and a depth of 5 meters. The geological soil stratification (see Fig. 2) consists of the following:
– First meter with dry gravelly sand above the water table level;
– Saturated gravelly sand layer under the water table from the second to the fifth meter;
– Clay lens from the fifth meter onwards.

The impervious layer of clay at the level of the excavation bottom is assumed to avoid seepage in the shaft, which could cause the instability of the bottom (piping phenomena). This excavation volume is the functional unit of the Life Cycle Assessment (LCA) analysis.

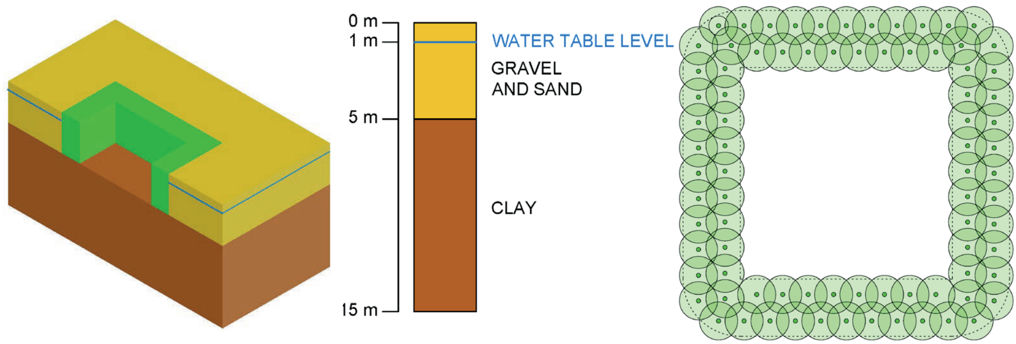

Fig. 2. Permeation grouting case study. The open-air excavation considered for the case.

The ground treatment is executed by placing 82 columnar elements through valved pipes, *tubes à manchette* (TAM) in the ground. The columns of treated soil have a radius of 75 cm and a plan distance of 1.2 m for a volume of treated soil equal to 472 m^3, deriving from a thickness of 2.50 m.

3.1. Phase 1: Qualitative Framing of the Sustainability Problem

In the first step, the framework that combines the Envision protocol [11] and the DNSH criteria is applied in line with the method proposed by [4] regarding the qualitative application of the framework and sustainability rating of the construction techniques. The protocol evaluation has been carried out by a certified Envision Sustainability Professional (certified under the Institute for Sustainable Infrastructure requirements and following the cited Manual).

In the case of a design experiment, those indicators that depend on the community and landscape context of a case study will be set to the minimum score allowed by Envision. Specifically, those indicators deepened through an LCA cradle-to-site analysis of the process will be appointed depending on the nature and limitations of the technologies, thus depending on the expected results from the LCA analysis. These values will be refined in phase three after the numerical analysis. This stage includes rating the indicators that should be made by designers or all actors involved in the inclusive decisional process, i.e., owners of the infrastructures, construction supervision bodies, public bodies, and citizen representatives. The engineers who designed the proposed soil consolidation solutions directly made the rate for the proposed case study.

3.2. Phase 2: Quantitative Analysis with LCA

The second step of the proposed method moves from qualitative to quantitative assessment by a specific cradle-to-site LCA analysis of the case study. An LCA starts with a definition of the aim and scope of the study and right after with the definition of the material stage. Its main effort resides in developing an inventory (LCI) in which all the significant environmental burdens from the lifetime of the product or process are quantified and compiled. This is followed by an impact assessment (LCIA) calculating and presenting the results in a predefined way that supports comparison or further analysis. LCA's concept and operational phases are described in the ISO14040 standards [12] and ISO14044 [13]. Fig. 3 highlights the boundaries and flows for the definition of the LCA study presented in this paper.

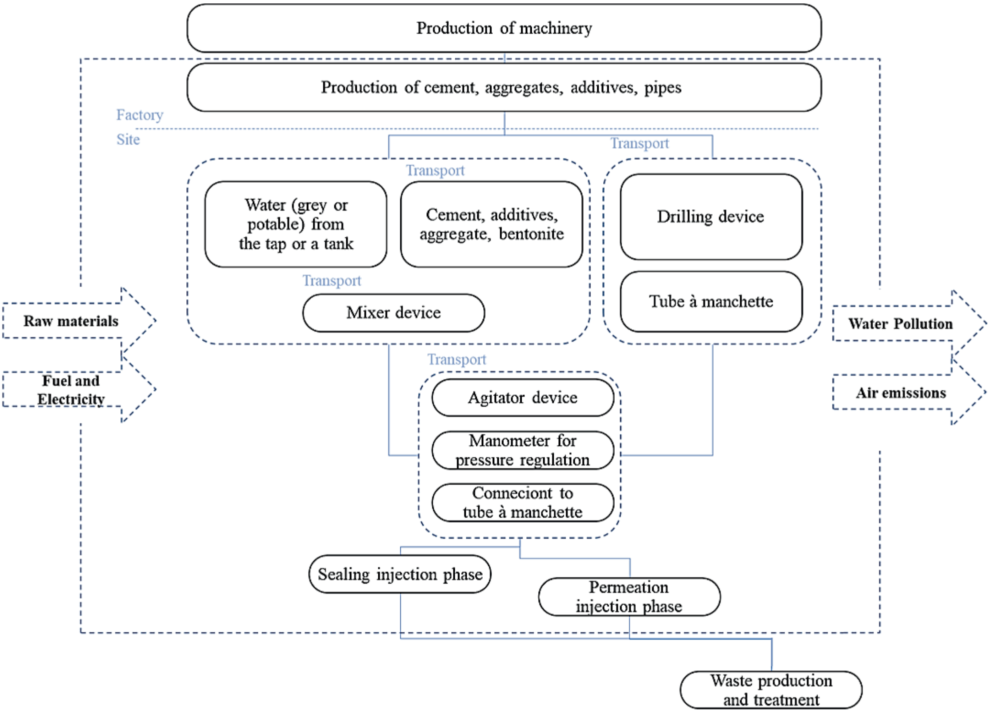

Fig. 3. Permeation grouting case study. Process scheme for the LCI and LCA modelling.

This modelling step is supported by the use of software *SimaPro* [14] to perform the LCA analyses. *SimaPro* is a commercial software for carrying out life cycle analysis. This tool was chosen because it is an industry-standard for processes and products. The database Ecoinvent 3.7 has been used as the inventory for the project, as implemented in *Simapro*. In order to focus the case study on process performance, it has been decided to standardize transports (when requested at the inventory level) with an average distance of 90 km. Table 1 provides the primary data for the case of permeation grouting as the core of the LCI.

TABLE 1. PERMEATION GROUTING CASE STUDY. LCI DATA

Materials	**Input**	**Value**	**Unit Measure**	***Simapro* Ecoinvent 3 Identifier**
PVC TAM	Product	320	Mass, kg	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | APOS, U (320 kg)
	Process	320	Mass, kg	Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U (320 kg)
	Transform	28 800	Distance, kg·km	Transport, freight, lorry 16–32 metric ton, euro5 {RER}| APOS, U (320 kg · 90 km)

Diesel Driller	Consumpt.	3200	Energy, kWh	Machine operation diesel, ≥ 74.57, underground mining (GLO), market for APOS, U (100 kW · 32 h)
	Product	6500	Mass, kg	Reference model CASAGRANDE C3-XP29
	Transport	585 000	Distance, kg·km	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (6500 kh · 90 km)
Electric mixing agitator	Consumpt.	370	Energy, kWh	Heat, air-water heat pump 10 kW {Europe without Switzerland}| market for floor heating from air-water heat pump | APOS, U (2.2 kW · 168 hr)
	Product	350	Mass, kg	Reference model LORENZETTO L500
	Transport	31 500	Distance, kg·km	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (350 kg · 90 km)
Turbomixer (electricity)	Consumpt.	1512	Energy, kWh	Electricity, medium voltage {IT}| market | APOS, U (9.0 kW · 168 hr)
	Product	350	Mass, kg	Reference model LORENZETTO L300
	Transport	31 500	Distance, kg·km	Transport, freight, lorry >32 metric ton, euro5 {RER}| APOS, U (350kg · 90km)
Electric injection unit mixture+ sheath (2 units)	Consumpt.	1848	Energy, kWh	Electricity, medium voltage {IT}| market | APOS, U (5.5 kW · 2 · 168 hr)
	Product	300	Mass, kg	Reference model LORENZETTO Elena 80/200
	Transport	300·274 = 82 200	Distance (kg·km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport| APOS, U (300 kg · 2 · 90 km)
Cement	Product	42 751	Mass, kg	Cement, Portland {Europe without Switzerland}| production | APOS, U
	Product	42 751	Mass, kg	Cement, pozzolana and fly ash 11–35 % {Europe without Switzerland}| cement production, pozzolana and fly ash 11–35 % | APOS, U
	Transport	3 847 590	Distance, kg·km	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport| APOS, U (42751 kg · 90 km)
Bentonite	Product	3671	Mass, kg	Bentonite {RoW}| quarry operation | APOS, U
	Transport	330 390	Distance, kg·km	Transport, freight, lorry 3.5–7.5 metric ton, euro5 {RER}| market for transport | APOS, U (3671 kg · 90 km)
Additive	Product	357	Mass, kg	Ethylene glycol monoethyl ether {RER}| production | APOS, U
	Transport	32 130	Distance, kg·km	Transport, freight, lorry 3.5–7.5 metric ton, euro5 {RER}| market for transport | APOS, U (357 kg · 90 km)
Water	Water from the tap	105 900	Mass, kg	Tap water {Europe without Switzerland}| market for | APOS, U
Mixture waste	Waste	6.36	Volume, m^3	Wastewater from concrete production {RoW}| treatment of, capacity 5E9l/year | APOS, U

The impact framework adopted in the analyses is the Environmental Footprint (EF) method 3.0, which originated from an initiative of the European Commission [15]. The method, supported by the *SimaPro* database, includes several adaptations, which make the implemented EF method 3.0 compatible with the data libraries provided in *SimaPro*. The scheme in Fig. 3 defines the boundaries of the analysis.

3.3. Phase 3: Revision, Validation and Integration within Envision

Once the LCA analysis is completed, the Envision assessment is revised. Specifically, the rating higher credits (more than 20 % of the maximum reachable target, that is, the basic entry level for Envision ratings) are refined in detail and finally defined.

4. RESULTS

4.1. Phase 1

The first trial of the scoring has been assigned based on the characteristics of the project, the five threshold requirements stated in the Envision protocol, and a preliminary hypothesis about the potential impact performance of the permeation grouting soil treatment.

As mentioned, for this case study, the engineers who designed the proposed soil consolidation solutions directly made the rating of the indicator as presented in the next Fig. 4. The radar diagram in Fig. 4 and Annex synthesizes the ratings. The radar diagram mainly shows how the best ratings focus on resource allocation, climate, and resilience.

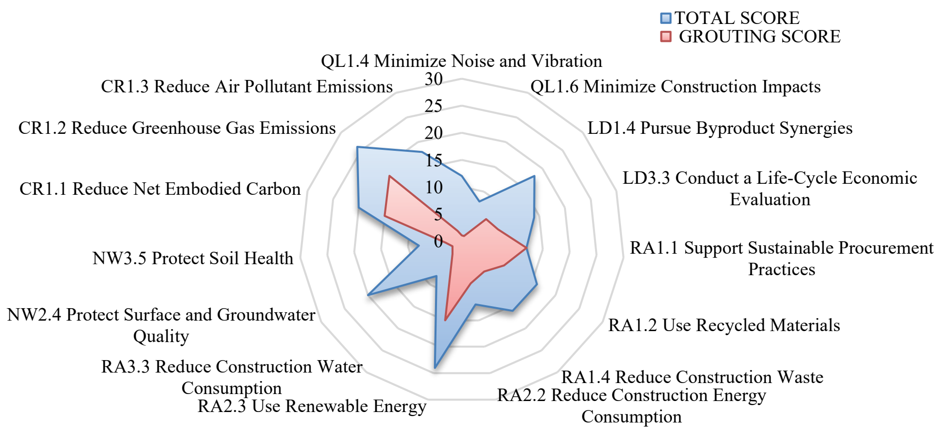

Fig. 4. Permeation grouting case study. Diagram of score contribution vs. each Envision indicator.

Compared to a maximum reachable of 232 points as from the Envison framework, this ground improvement process scored 109 points (an overall value of 47 %). However, when confirmed by the LCA analyses, this could be considered a good score (rewardable with a ‘gold’ rating following Envision rating scale).

4.2. Phase 2

The results of the LCA analysis of the permeation grouting case study are now reported and commented on in the graphical form (see Fig. 5) according to the impact assessment method EF 3.0. The LCA characterization phase of the analysis models categories in terms of indicators and provides a basis for aggregating the inventory input and output within the category. Fig.5 presents the permeation grouting steps (grout mix preparation, grout mix injection, drilling, and TAM positioning and transportation) versus the impact categories in the characterization stage of the LCA. The grouting mix's role is evident compared to the other steps. Still, this plot allows realizing that climate change, which often is the reference impact in sustainability reports, is just one of the possible and critical impacts.

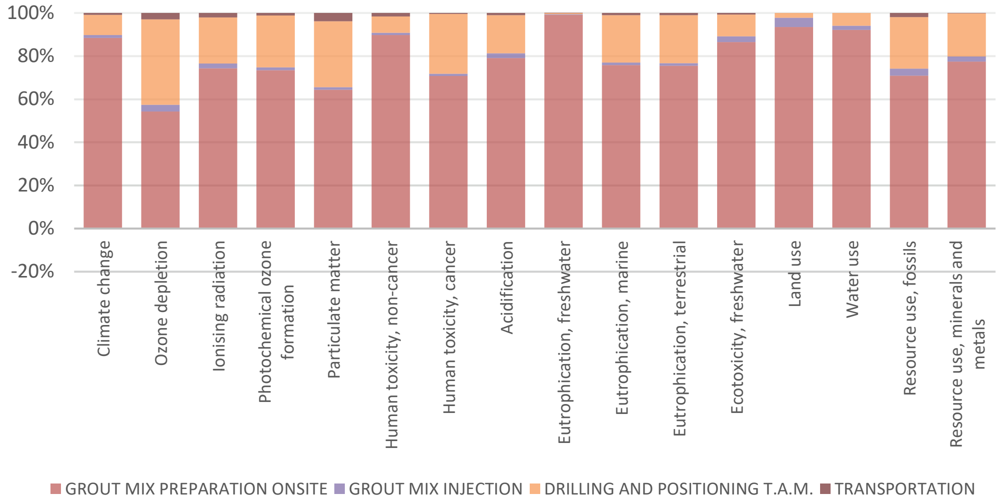

Fig. 5. Permeation grouting case study. Impacts, characterization view.

This information is relevant considering the more significant role in materials, quantities, and energy that the grouting preparation phase plays concerning the others. The development of the analysis will make it possible to understand which impact category is more relevant than the others. The following graph shows the final scores for the endpoints expressed in terms of ecological point (i.e., Pt).

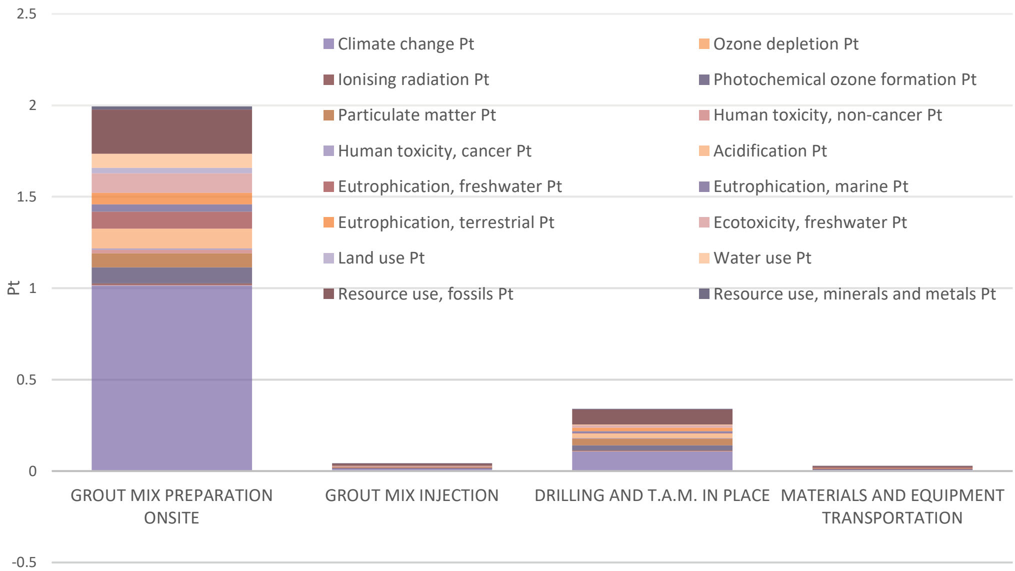

Fig. 6. Permeation grouting case study. Impacts at ecological Point (Pt).

The analysis of the grout mix preparation is performed to further study the relevance of each phase in the impact scenario. The following graph (Fig. 7) represents the single score impact view for the subcase of the grout mix preparation on site. This figure allows an understanding of the role played by the single components of the grout mix. As expected, cement is the most impactful material.

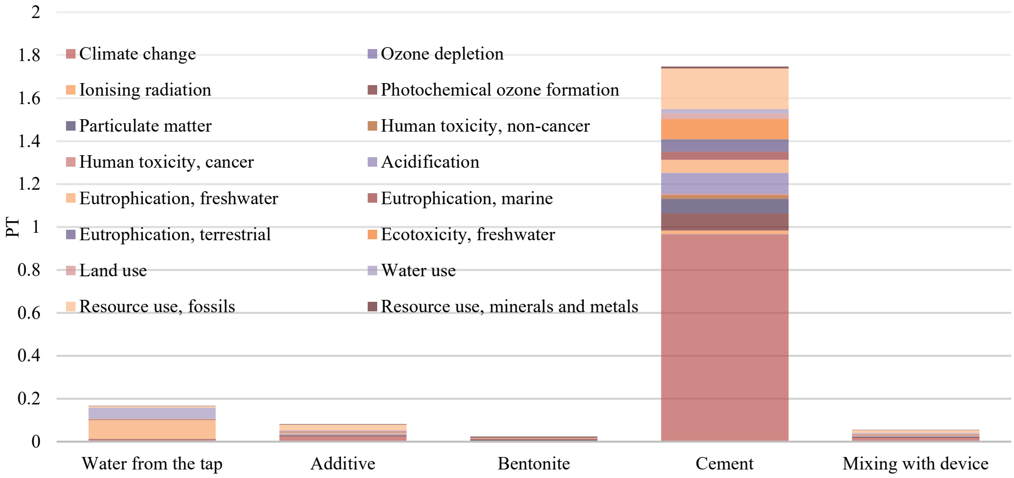

Fig. 7. Permeation grouting case study. Grout mix preparation, impacts, single point view.

Table 3 summarises the impact in percentages for the permeation grouting case study, which will be used in the third phase for fine-tuning the sustainability assessment framework.

TABLE 3. CASE STUDY PERMEATION GROUTING – GROUT MIX PREPARATION, IMPACT PERCENTAGES, SINGLE POINT

Impact category	Unit	Total	Grouting Mix	Injection	Drilling	Transport
Total	%	100.0	83.3	1.8	13.9	1.1
Climate change	%	46.1	40.8	0.6	4.4	0.4
Ozone depletion	%	0.1	0.1	0.0	0.1	0.0
Ionising radiation	%	1.0	0.8	0.0	0.1	0.0
Photochemical ozone formation	%	4.7	3.5	0.1	1.1	0.1
Particulate matter	%	4.8	3.1	0.1	1.5	0.2
Human toxicity, non-cancer	%	0.9	0.8	0.0	0.1	0.0
Human toxicity, cancer	%	0.4	0.3	0.0	0.1	0.0
Acidification	%	5.5	4.3	0.1	1.0	0.1
Eutrophication, freshwater	%	6.6	6.3	0.1	0.2	0.0
Eutrophication, marine	%	2.3	1.7	0.0	0.5	0.0
Eutrophication, terrestrial	%	3.3	2.5	0.0	0.7	0.0
Ecotoxicity, freshwater	%	4.9	4.3	0.1	0.5	0.0
Land use	%	1.3	1.2	0.1	0.0	0.0
Water use	%	3.4	3.2	0.1	0.2	0.0
Resource use, fossils	%	13.6	9.6	0.4	3.3	0.3
Resource use, minerals and metals	%	1.0	0.8	0.0	0.2	0.0

Based on the performed study, the following interpretation of the results can be drawn regarding cement injection technology:

1. The most impacted categories are climate change and resource depletion;
2. The impact of the mixture compared to the total equals 83.3 %. In comparison, the other relevant contribution is given by drilling with 13.6 %. Further optimization of the LCA analysis could focus on these two directions.

4.3. Phase 3

This last phase aims to combine all the contributions and review the Envision framework results. The LCA results are integrated within the scoring of the Envision framework. Hence, design and construction strategies aimed at enhancing environmental performance can be recognized as a sustainable and sound design approach. The following section analyses each of the relevant Envision indicators listed in phase 1. The assessment of the phase scores is done through the results of the LCA model (Table 3 and previous figures).

4.3.1. Life-Cycle Economic Evaluation

Envision requires a Life-Cycle Cost Analysis (LCCA) to be conducted on the project to identify its total economic impact. LCCA compares and assesses alternatives for at least one major design component [6]. Considering that the LCA requires detailed information and knowledge on material quantities and energy consumption, it is assumed that a detailed cost analysis for the cradle-to-site context is available. Finally, 50% of the scoring can be confirmed.

4.3.2. Support Sustainable Procurement Practices

The analysis makes it possible to identify the environmental performance of each project's materials, supplies, and equipment and check whether they meet the sustainable procurement policy/program requirements. There are two levels of impact to be taken into account:

- The relevance of the project in itself from gate to site, where the machinery on site is responsible for 13.6 % of impact (with 4.4 % belonging to climate change, 3.3 % to fossil resource use, and 1.5 % to particulate matter);
- The level of the products (cement mainly) accounts for 83.3 % (with 40.8 % belonging to climate change, 9.6 % to fossil resource use, 8 % to water eutrophication and acidification, and 3.1 % to particulate matter), while less is due to transportation (1.1 % impact overall). In this case, the design should require cement mixtures different than Portland (pozzolanic, fly ash based, etc., or clinker production with reduced energy consumption) and for contractors that ensure transportation fed with biofuel or machinery operated with electric power. Considering that the use of "green" cement is already becoming a relatively common practice and that the grout mix provides for more than 50 % of the impactful products, the score given to this credit can be confirmed.

4.3.3. Use Recycled Materials

To reach at least 25 % (by weight, volume, or cost) of recycled materials, including materials with recycled content and/or reused existing structures or materials, the material to focus on is cement and grout. Concrete with recycled aggregates should be procured (for example, using aggregates from recycling processes like steel-mills secondary products, aggregated from concrete items' demolition, etc.). The same can be done for cement. Another option can be made of recycled steel or plastics, eventually biodegradable. Provided that these options are implemented, the score can be confirmed.

4.3.4. Reduce Construction Energy Consumption

To implement energy reduction strategies, at least four design choices can be made: cement from a green supply chain, use truck EURO6 or better, use of machinery for mixing powered by electricity, and choose recycled aggregates for concrete.

4.3.5. Use Renewable Energy

There could be three possible scenarios to ensure that the project meets 50 % of energy needs (electricity and fuel) from renewable sources: (a) cement comes from a supply chain that uses renewable energy or low content of clinker, (b) the site work uses electric power and chooses a provider for electricity that has a 50 % of renewable sources, (c) the transportation is fueled with biofuels. Provided that these options are implemented, the score can be confirmed.

4.3.6. Reduce Net Embodied Carbon

The project team must demonstrate at least a 30 % reduction in total embodied carbon of materials over the project's life compared to the baseline. In this case, again, cement and aggregates are the leverages. One more possibility comes from the TAM that could come from recycled plastics. Provided that these options are implemented, the score can be confirmed.

4.3.7. Reduce Greenhouse Gas Emissions

To reach the score, the project team must demonstrate at least a 50 % reduction in total CO_2eq over the project's operational life compared to the baseline. The project team has to map and calculate the final project design's total annual greenhouse gas emissions for reporting purposes. The LCA calculation could provide this information because of green cement and aggregates. The impact of cement on climate change using "green" cement should be reduced significantly, but quantifying this reduction is difficult to do. The authors are conducting further analyses to catch the information from cement and concrete producers' Environmental Product Declaration [16]. This means that the score must be decreased because, at the moment, the project does not permit such a reduction. Scaling back one step means this goes to 13 and the percentage to 50 %.

4.3.8. Pursue By-product Synergies

This indicator requires that candidates for by-product synergies or reuse are identified. This can include finding beneficial reuse for the project's waste or excess resources or the reuse of external waste or excess resources. Project teams should also consider ecosystem services where project waste or excess resources can support natural systems or where natural systems can process and remove project waste. The design and the LCA show that the only waste produced is sludge from the injection process. This sludge is supposed to be collected and dried (with a portable filter press system). The liquid part is then purified (directly on-site or transported to a water treatment facility), and the dry part is reused as construction filling material. The score is confirmed because analysis can be performed, and at least one by-product is identified and used.

4.3.9. Reduce Construction Waste

In this case, the project team has to set a target goal for construction waste diversion. At least 50 % of waste materials are recycled, reused, and/or salvaged during construction. Diversion may combine waste-reduction measures and sourcing waste to other facilities for recycling or reuse. As the previous indicator said, the primary waste product is sludge, and collection and recycling are possible. It also has to be considered that TAM in itself will stay in the ground after the injection; if self-degrading bioplastics are used (see, for instance, Durvinil Biosystem [17], where a high rate of biodegradation is expected), this can be considered as a waste reduction measure, and the score can be confirmed.

4.3.10. Reduce Construction Water Consumption

To implement at least one potable water conservation strategy, grey water should be used during the mixing and injection phases.

As this assessment concluded after the LCA analysis, only one score had to be revised (CR.1.2). The overall scoring goes to 104/232 (45 %), which still ranges high (gold rating).

After applying these refinements, the final scoring of the framework is shown in the Table 4.

TABLE 4. CASE STUDY PERMEATION GROUTING. ENVISION VS. DNSH REVISED RATINGS

					Scored EU environmental targets Permeation Grouting					
	Max. ENVISION Points Available	**Min. ENVISION Points Available**	**Score Permeation grouting**		**Climate Change mitigation OBJ 1**	**Climate Change adaptation OBJ 2**	**Sustainable use of water and marine resources OBJ 3**	**Circular economy transition OBJ 4**	**Pollution prevention OBJ 5**	**Biodiversity and ecosystem protection OBJ 6**
QL1.4	12	1	1	8 %	0	0	0	0	0	0
QL1.6	8	1	1	13 %	0	0	0	0	0	0
LD1.4	18	3	6	33 %	0	0	0	6	6	0
LD3.3	14	5	7	50 %	0	0	0	0	0	0
RA1.1	12	3	12	100 %	0	0	0	12	12	12
RA1.2	16	4	9	56 %	9	0	0	9	0	0
RA1.4	16	4	7	44 %	7	0	0	7	0	0
RA2.2	12	1	8	67 %	8	0	0	0	0	0
RA2.3	24	5	15	63 %	15	0	0	0	0	0
RA3.3	8	1	3	38 %	0	0	3	0	0	0
NW2.4	20	2	2	10 %	0	0	2	0	2	2
NW3.5	8	3	3	38 %	3	0	0	0	3	3
CR1.1	20	5	15	75 %	15	0	0	15	0	0
CR1.2	26	3	13	50 %	13	0	0	0	0	0
CR1.3	18	2	2	11 %	0	0	0	0	2	0
Envision	**232**	**43**	**104**	**45 %**	**70**	**0**	**5**	**49**	**25**	**17**
DNSH	**348**	**68**	**166**	**244 %**						

5. DISCUSSION, RECOMMENDATIONS, AND CONCLUSIONS

This paper aims to show the detailed implementation of a case study for applying the three-phased framework to assess the sustainability of a construction process and, in particular, of a ground improvement application through permeation grouting. The three-phased method, described in a background paper proposed by Pettinaroli and Susani [4] has the scope to support the construction industry and the decision makers (i.e., investors, owners, designers, constructors, suppliers, technology developers, and producers) in making construction choices with an explicit sustainability metric in mind at both the strategic and the implementation level. This is an essential approach for the project's general view and the primary and critical construction processes in a way that can be transparently shared and used to claim for truly sustainable measures adopted in their projects.

After implementing the third phase of the proposed method (i.e., after the scoring refinement of phase 3), the stakeholder can have a detailed view of each Envision credit scoring and an overview of the full results. The sustainability rating of the case study ranks around 45 % of the maximum reachable scoring, which is a "gold" performance compared to the Envision scale. In parallel, the framework produces a view on the DNSH EU criteria compared to a minimum of 68 points. The case performed 166, which means 144 % more than the minimum requirement of the EU regulation. With the same approach, more than one technology can be compared based on a common metric [4]. Thanks to the LCA performed, providing a common grading baseline and refining the first screening is possible. Adopting an LCA brings more profound knowledge and the quantitative analysis needed to size the assessment. The range of impacts and the opportunity to compare different construction strategies (i.e., material and technology adoption, timing, schedule, phasing, etc.) allows for a fine-tuning of the process from the environmental point of view. It can genuinely identify critical and hot points that could stimulate the industry through transparent indicators/requirements available for the procurement criteria of contractors and owners. Still, the social and economic components are embedded in the protocol application but not investigated at this study stage.

This research emphasized the role of the LCA as a standard and consistent frame through which owners and the construction industry can make measurable, suitable, and sustainable moves.

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ANNEX

PERMEATION GROUTING CASE STUDY – THE ENVISION/DNSH FRAMEWORK EVALUATION FOR THE CASE STUDY, ASSIGNED SCORES AND MAXIMUM AVAILABLE SCORES

Indicator (credit)	Section	Metric	Criteria	Score	%	Max
QL1.4 Minimize Noise and vibration	Quality of life: wellbeing	The extent that operational noise and vibration is assessed and mitigated, and target levels achieved.	The project team assesses the potential for operational noise impacts on the surrounding community and/or environment. This assessment occurs when applicable vibrations are considered as a potential source of noise and/or disruption.	1	8	12
QL1.6 Minimize ConstructionI mpacts	Quality of life: wellbeing	Extent of issues addressed through construction management plans.	The project team implements a construction management plan or policies to address the temporary inconveniences associated with construction. The plan or policies are informed by stakeholder engagement.	1	13	8
LD1.4 Pursue Byproduct Synergies	Leadership: collaboration	The extent to which the project team works with external groups to find beneficial use of waste, excess resources, or capacity.	Candidates for byproduct synergies or reuse are identified. This can include finding a beneficial reuse for the 'project's waste or excess resources, or the 'project's beneficial reuse of external waste or excess resources.	6	33	18
LD3.3 Conduct a Life-Cycle	Leadership: economy	The comprehensiveness of the economic analyses used to determine the net impacts of the project, and their use in assessing	LCCA is used to compare and assess alternatives for at least one major design component.	7	50	14

Indicator (credit)	Section	Metric	Criteria	Score	%	Max
Economic Evaluation		alternatives to inform decision making.				
RA1.1 Support Sustainable Procurement Practices	Resource allocation: materials	The extent of sustainable procurement programs, and the percentage of materials sourced from manufacturers and/or suppliers that implement sustainable practices.	At least 25 % of all project materials, supplies, and equipment meet the sustainable procurement policy/program requirements.	12	100	12
RA1.2 Use Recycled Materials	Resource allocation: materials	Percentage of project materials that are reused or recycled. Plants, soil, rock, and water are not included in this credit.	At least 25 % (by weight, volume, or cost) of recycled materials including materials with recycled content and/or reused existing structures or materials.	9	56	16
RA1.4 Reduce Construction Waste	Resource allocation: materials	Percentage of total waste diverted from disposal.	The project team sets a target goal for construction waste diversion. During construction at least 25 % of waste materials are recycled, reused, and/or salvaged.	7	44	16
RA2.2 Reduce Construction Energy Consumption	Resource allocation: energy	The number of strategies implemented on the project during construction that reduce energy consumption and emissions.	The project implements, or has written requirements to implement, at least four (4) energy reduction strategies.	8	67	12
RA2.3 Use Renewable Energy	Resource alloc.: energy	Extent to which renewable energy sources are incorporated.	The project meets: 30 % of energy needs (electricity and fuel) from renewable sources.	15	63	24
RA3.3 Reduce Construction Water Cons.	Resource alloc. water	The number of strategies implemented during construction that reduce potable water consumption.	At least one (1) potable water conservation strategy is implemented.	3	38	8
NW2.4 Protect Surface and Groundwater Quality	Natural world: conservation	Designs, plans, and programs instituted to prevent and monitor surface water and groundwater contamination during construction and operations.	(I) The project team determines potential impacts to surface water or groundwater quality. (II) The project includes spill and leak diversion systems, spill prevention plans, and clean-up.	2	10	20
NW3.5 Protect Soil Health	Natural world: ecology	Degree to which the disruption of soil health has been minimized and restored.	100 % of post-construction vegetated areas disturbed during construction are restored for appropriate soil type, structure, and function to support healthy plant and tree growth.	3	38	8
CR1.1 Reduce Net Embodied Carbon	Climate and resilience: emissions	Percentage of reduction in net embodied carbon of materials.	The project team demonstrates at least a 5 % reduction in total embodied carbon of materials over the life of the project compared to the baseline.	15	75	20

Indicator (credit)	Section	Metric	Criteria	Score	%	Max
			Calculations should be in tons CO_2.			
CR1.2 Reduce Greenhouse Gas Emissions	Climate and resilience: emissions	Percentage of reduction in operational greenhouse gas emissions.	(I) The project team demonstrates at least a 25 % reduction in total CO_2e over the operational life of the project compared to the baseline. Calculations should be in tons CO_2e. (II) The project team maps and calculates the total annual greenhouse gas emissions of the final project design for reporting purposes.	18	69	26
CR1.3 Reduce Air Pollutant Emissions	Climate and resilience: emissions	Reduction of air pollutants compared to baseline.	(I) The project meets all applicable air quality standards and regulations for air pollutants. (II) The project implements strategies to reduce air pollutant emissions during operations.	2	11	18
				109	47	232