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A Sustainability-Based Approach for Geotechnical Infrastructure

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Abstract **– Urban growth needs large cities, and the current emphasis on landscape preservation makes using underground spaces an opportunity and a significant necessity. However, underground construction techniques significantly impact the sustainability of the built environment, including infrastructure systems and their entire supply chains. Nowadays, there is a shortage of quantitative methodologies to assess and measure the sustainability of construction and underground building processes towards the three sustainable pillars, i.e. environmental, social, and economic. Thus, this study aims to cover this gap by explaining how to appropriately incorporate sustainability goals into geotechnical projects to address measure-driven strategies and eco-design-based solutions. This study illustrates a novel methodology based on the Life Cycle Thinking approach, with an emphasis on geotechnical ground improvement techniques. The proposed method incorporates the concept of the EU Taxonomy, following the EU Green Deal, with the Envision framework to guide decision-makers toward a more sustainable, resilient, and equitable infrastructure design. The proposed method will incorporate a cradle-to-site Life Cycle Assessment perspective, improving the quantitative estimation of the environmental performance of construction processes and providing guidelines to systematically assess the sustainability of geotechnical infrastructures.**

Keywords **– Built environment; eco-design; geotechnics; LCA, life cycle thinking; sustainability; transportation infrastructure.**

1. INTRODUCTION

1.1. Sustainability in Geotechnics

The urbanization of the planet is accelerating. This trend, together with population growth and resource scarcity, dynamically affects the need for new infrastructures in conjunction with a more relevant necessity for renovating the existing assets. This often results in the creation of underground urban planning strategies to manage a variety of current flows (i.e., people, goods, water, energy, waste, etc), making the exploitation of underground infrastructures a key priority [1]. Although the techniques used to build these infrastructures

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are becoming more advanced and efficient, sustainability and environmental footprint do not follow the same trend. In particular, the tools for an integrated assessment of the sustainability in social, environmental, and economic terms, are limited because the underground engineering environment is a rather young field of engineering and need to be calibrated on specific needs, in other words it can be defined as prototypical field of engineering and science [2].

The EU Green Procurement System supports this transition. It represents a mechanism to encourage the construction industry to refer to operational decisions, i.e., technological, productive, and organizational, based on optimising and reducing the overall environmental footprint aligned with the corporate sustainability strategy [3]. This study aims to develop and describe a novel methodology to evaluate the sustainability of ground improvement and geotechnical works, emphasizing the environmental dimension. The proposed methodology integrates the UE Green Deal concepts implemented in globally recognized sustainability rating protocols and quantitative analytical methods for environmental footprint assessment.

1.2. Sustainability in Ground Improvement Techniques

Geotechnical engineering must include a core practice focused on environment-friendly and resource-efficient strategies to contribute to sustainable development. This is addressed explicitly to geotechnics towards selecting construction materials and technology that can contribute to reducing the impact. Thus, a holistic and consistent sustainability assessment framework is essential. This has already been stressed for geotechnical projects to ascertain the relative merits of different options available for underground construction projects [4]. With their diversity and growing variability of needs and technologies, ground improvement techniques represent an ideal testing field for a sustainability-based design approach. On the one hand, there is the need to focus on the efficiency of the processes and the technologies, while on the other hand, there is a complex variety of materials (sometimes very innovative) involved.

The case study developed in detail in a parallel paper from the authors [5] illustrates the proposed sustainability assessment methodology. Specifically, the proposed geotechnical project focuses on implementing Permeation Grouting technology to waterproof and stabilize an open-air excavation below the water table in Milan. Ground improvement grouting techniques aim to strengthen the soil mass and reduce its permeability by injecting a pumpable slurry or grout to fill the voids between soil grains. Based on appropriate operational conditions, the grouting activity fills the voids between the soil particles without appreciable displacement of the surrounding material. The process is called permeation grouting. The design of the fluid mix is typically cement-based with specific additives, depending on the soil characteristics to improve. The fluid is injected into the soil through PVC valved pipes, i.e., *tubes à manchette* (TAM).

1.3. The EU Regulatory Framework as a Point of Reference

The 2015 Paris Climate Agreement results from several stakeholders' global efforts to promote sustainable development to mitigate climate-driven risks and their impact on assets and financial institutions. It emphasizes the need to direct financial resources toward climate-resilient development and the United Nations 2030 Agenda for Sustainable Development, which lays out 17 Sustainable Development Goals (SDGs) linked to environmental, social, and governance (ESG) presumptions and requirements [6].

In December 2019, the European Commission launched the European Green Deal, a legislative and regulatory action plan focused on climate change and coping with a broad range of environmental-related challenges. The EU Green Deal delineates a new growth strategy that aims to transform the EU into a resource-efficient and competitive economy with no net greenhouse gas emissions by 2050 and a 50/55 % reduction by 2030, making Europe the first climate-neutral continent. This aim requires hundreds of billions of investment turnaround for the years to come and, thus, a solid legal and regulatory framework underpinning sustainable financing [7].

To this end, in 2016, a High-Level Expert Group on Sustainable Finance (HLEG) was appointed by the EU Commission to develop an EU roadmap on sustainable finance to leverage the allocative role of financial markets to build the world's most sustainable financial system. The HLEG identified the establishment of a common European sustainability taxonomy framework as a priority. This common 'green' classification system provides clarity and guides market participants on what investments or financial products will contribute to the EU's sustainability objectives, ensuring comparability across standards and products altogether and ultimately fostering economic growth. In June 2020, the European Parliament and the Council adopted Regulation (EU) 2020/852 '*on the establishment of a framework to facilitate investment and amending Regulation (EU) 2019/2088*', which entered into force in July 2020 [6].

To trace the contours of what is environmentally sustainable, the article 9 of the Taxonomy Regulation lays out a list of the following six main environmental objectives:

- Climate change mitigation, i.e., the process of holding the increase in the global average temperature to well below 2 ºC and pursuing efforts to limit it to 1.5 ºC above pre-industrial levels;
- Climate change adaptation, i.e., the process of adjustment to actual or expected climate change and its impacts;
- Sustainable use and protection of water and marine resources;
- Transition to a circular economy;
- Pollution prevention and control;
- Protection and restoration of biodiversity and ecosystems.

Considering the above, under Article 3 of the Regulation, an economic activity shall qualify as environmentally sustainable where it meets – cumulatively – the four following conditions:

- Contributes substantially to at least one environmental objective;
- *Do no significant harm* (DNSH) to any other environmental objective;
- Complies with minimum social safeguards defined on a local national basis;
- Complies with applicable technical screening criteria defined locally and nationally.

The EU taxonomy framework provides the construction industry with a general criterion for assessing sustainability, a precondition to access funding and financial leverage.

The DNSH criteria that assess compliance to the six environmental objectives is quickly becoming the sustainability criterion in the construction industry at all levels and for any technology.

1.4. The International Sustainability Protocols for Infrastructures

Holistic sustainability protocols for infrastructure and construction industry sectors have gained momentum in the last decade. There are different reasons justifying this trend: the infrastructure construction industry has been conservative and unwilling to change. In fact, infrastructure often belongs to public owners, safety, cost control, and operational performance, representing a complex set of drivers when choosing and designing construction processes primarily through public procurement.

Nevertheless, with the need for sustainable development and green construction in recent years, green building rating systems have been developed to measure building life cycle performance. These certifications have been implemented in methodological design approaches in the building industry e.g., BIM, LEED, Lean, and Green Building Council [8], transforming the way how cities and communities are designed, created, and operated to improve people's quality of life worldwide.

These programs offer a framework for planning, designing, measuring, and managing social, economic, and environmental issues at the city- or community level. The United States Green Building Council (USGBC) created the Leadership in Energy and Environmental Design (LEED) rating system, making its application in design, credit analysis, and documentation—which must be submitted in order to obtain the necessary kind of credentials—significant in the research community [9].

Site selection, waste reduction, energy and atmosphere, resources and materials, interior environment quality, locations and linkages, design innovation, and regional significance are all given points by LEED through an online scoring system. Successful project outcomes are incorporated and given a certification such as Certified, Silver, Gold, or Platinum.

Modern buildings are designed with the Building Information Modelling (BIM) technique. The architectural, engineering, and construction (AEC) industry sees it as a huge possibility since it is an end-to-end platform and process. One of the most exciting advancements in the architectural, engineering, and construction (AEC) industry is building information modeling (BIM), which provides a collaborative platform for accurate digital modeling of construction projects in virtual environments. The development of BIM as a system has made it possible to integrate and manage information throughout a building's existence, making it possible to use existing design data for planning and performance analysis that is both sustainable and effective. The designer applies tools to her BIM to create a 3D model of the structure where design materials will be used.

Similarly, Lean principles are applied in the construction industry to reduce waste and improve the construction process. Waste has a negative effect on the environment and reduces productivity. Although '*waste-to-resources*' and '*energy-waste*' have been shown to be more suitable waste solutions, they can increase project costs and cause additional environmental problems. Lean construction has also become more widely adopted and used in recent years.

Lean Thinking suggests a method for '*doing more with less*' (i.e. less time, money, resources, and space) and focuses on delivering what truly adds value to customers while minimizing waste through more effective processes that maximize the key production value chain competencies [10]. According to Salehi (2015) [11], Lean thinking functions as a transformative system that operationalizes organizational learning and fosters innovation, allowing businesses to manage their limited resources.

Numerous techniques and tools have been researched and created to improve the construction process so that it is easier to manage, safer, completed sooner, has better quality, and costs less than traditional ones. These techniques and tools were developed based on the lean thinking approach and reports stating that the construction industry is one of the least efficient. However, even though lean initiatives require less space for operation and storage, which, when combined with a production that is less prone to defects, decreases the use of energy and resources, thus promoting significant environmental advantages [12], such methods may need to be modified to address current environmental challenges [13].

Lean Construction has lately been combined with other methodologies like BIM due to the synergy of improving construction processes and reducing waste. There is a great opportunity to increase productivity and efficiency while boosting sustainability in the context of BIM and Lean goals. By incorporating BIM, Lean, and sustainability practices inside their organizations, many enterprises in the construction sector have the chance to revolutionize how they conduct their operations. Because a proper integration requires counting using this technique. There is much opportunity to boost productivity and efficiency while enhancing sustainability in the context of BIM and Lean aims.

Some Western Countries (UK, Germany, Australia, US) started to develop dedicated frameworks after 2010 [14], like the voluntary Envision protocol developed in the US by the Institute for Sustainable Infrastructures in collaboration with Harvard University [15]. This is also expanding in the EU context. Among the other EU member countries, in Italy, the protocol is implemented as a sector reference, with examples in various leading infrastructure systems: railway, electric grid, renewables, power generation, roads and highways, and urban subways.

Envision is a framework that provides the guidance needed to initiate systemic change in the planning, design, and delivery of sustainable and resilient infrastructure, as requested by the EU Green Deal. This framework includes 64 sustainability and resilience indicators, called 'credits', organized around five categories: Quality of Life, Leadership, Resource Allocation, Natural World, and Climate and Resilience. These indicators collectively address human well-being, mobility, community development, collaboration, planning, economy, materials, energy, water, siting, conservation, ecology, emissions, and resilience [15]. Each of the 64 credits has multiple levels of achievement representing the spectrum of possible performance goals, from slightly improving beyond conventional practice to conserving and restoring communities and environments. By assessing the achievement in each credit, it can be evaluated how well a certain project addresses the full range of sustainability indicators and which are the more challenging to pursue higher performance.

On the other hand, the advent of Building Information Modelling (BIM) in the construction sector has altered how projects are handled and carried out. Using the LEED approach, eventually in combination with BIM, may allow designers to save project costs, boost productivity, and improve safety, ensuring a project satisfies the highest sustainability and environmental friendliness criteria.

The challenge of infrastructural systems is to reach a compromise between adequately and comprehensively addressing the principles of sustainability and providing a scheme that is understandable and accessible to clients and professionals. In their study, Griffiths *et al.* (2018) [16] conclude that assessment tools of this nature and type are crucial in disseminating sustainability knowledge and practices among the subjects who use them in projects, in the communities with which they interact, and within the organizations for which they work. The impacts of infrastructure sustainability assessment tools are not limited to projects undergoing assessment and certification (i.e., their formal use) but extend to the entire infrastructure sector through their informal use at individual, organizational, and sector.

Nevertheless, there is still a lack of integrating or combining these methods with more standardized environmental performance assessment and environmental design. Thus, integrating with LCA methodology can be an effective and powerful way to successfully execute infrastructural and construction projects.

1.5. The State of the Art for LCA and LCCA Analyses in Geotechnics

Geotechnical engineers may not be that familiar with making environmental impact assessments in their daily work; still, there is a broad literature about it, including general soil stabilization [2], foundation support [17], [18], land remediation or environmental containment [18], and flood protection [17]. As said, the size of the investment cost is the most crucial factor when deciding if a construction project is being realized. Nevertheless, decisions in a geotechnical engineering project affect the environmental impact and monetary cost during the structure's life cycle. Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) are established methods for assessing such environmental impacts and monetary costs from construction works. The results can be used to make decisions to reduce the environmental impact and monetary cost of geotechnical engineering projects. However, limited research has been published on applying LCA and LCCA to geotechnical engineering. For example, Jefferis *et al.* (2008) [19] found a lack of specific guidelines on implementing sustainability in geotechnical engineering.

An LCA starts with a definition of the aim and scope of the study. Its main effort resides in developing an inventory (LCI) in which all the significant environmental burdens from the lifetime of the product or process will be quantified and compiled. This is followed by an impact assessment (LCIA) calculating and presenting the result in a predefined way that supports comparison or further analysis. LCA's concept and working phases are described in the ISO14040 [20] and ISO 14044 [21].

Life Cycle Costs (LCC) is a quantitative approach that accounts for all of the costs incurred over a product's life cycle, those of the owner or producer, defined as capital costs (i.e. CAPEX) and the operating ones (i.e., OPEX). LCCA has become aligned with LCA and developed into a code of practice [22]. There are different types of LCC: financial LCC, also called conventional LCC, according to the ISO 15686-5:2017 standard [23], environmental LCC, and societal LCC [24] depending on how external environmental and societal costs are 'internalized' in a financial LCC.

2. SUSTAINABILITY IN GEOTECHNICS: TAILORING A COMBINED METHOD

2.1. Phase One: Tailoring a Combined Method

The EU regulation requires an explicit analysis to establish whether an economic activity could be considered significantly harmful through the already introduced frame of the DNSH criteria and taking into account the life cycle of the products and services it provides, including evidence from existing life-cycle assessments. When assessing an economic activity against the six targets set in section 1.3, both the environmental impact of the activity itself and the environmental impact of the products or services provided throughout its life cycle have to be taken into account, in particular by considering the production, use, and end of life of those products and services.

The regulator aims to force investors, owners, designers, and constructors to set up a sustainability strategy for their projects instead of just generic purposes or a scattered series of environmentally friendly actions. At the same time, as designers, we think that pure compliance verification against the six targets will not support the decision-makers in evolving the nature of their projects. This is why we suggest, as a first step, adopting a general sustainability rating protocol for the project based on consistent and well-recognized indicators within a comprehensive, sustainable, and structured approach that properly combines performance and economic needs with social and environmental perspectives. The Envision protocol could support this specific need.

The Envision protocol [15] is well-structured and solid. It allows a simple preliminary approach that is very useful in this framing phase. This can be done by selecting the applicable indicators and identifying the appropriate leverages that play a critical role in sizing the sustainability rating of the project. This phase is crucial because it allows a fine-tuning of the project's general strategy and focuses the attention of the stakeholders on the environmental and social hotspots, apart from the technical performance or the cost in itself. With this first framing, the focus on a sustainability strategy of the project will be strong and more accessible to share among the stakeholders.

The application of Envision is also helpful in light of the EU Taxonomy. Following the path traced by ICMQ [25], it is possible to identify a connection between the Envision indicators and the six targets listed in Article 3 of the cited EU Regulation. This is a straightforward way to check the project against the DNSH criteria, adopting the Envision analysis as a reference metric for EU compliance. Nevertheless, there is a fundamental integration: while the DNSH assessment deals only with the environment, the Envision protocol also considers the economic and social aspects, thus satisfying the three ESG factors. Most of the Envision credits directly impact the objectives indicated in the 2020/852 Regulation. Within the protocol, additional credits contribute indirectly but effectively to achieving the objectives.

Following our professional experience and being aware of the construction industry's needs, we connected the ‘views’ of the EU regulation (that will set the stage for the following years) with a sustainability metric as the one that Envision declines through its protocol.

Moving from DNSH of EU Taxonomy to Envision, the entire set of Envision credits (64 overall, divided into 5 categories, as said) to identify the correspondences between the Envision approach and the UE requirements is in-depth explored.

The lines with the applicable Envision credits in each category have been crossed with each of the 6 EU objectives and with each of the subcases cited in the Regulation (and listed above). This way, once the score is assigned to a credit, its value will be fully tracked under the DNSH evaluation.

In the first category, Quality of Life, we improved the cited approach of ICMQ [25] and then reduced the number of applicable credits to our specific ground improvement case. The 13 credits for quality of life have few connections with the EU sustainability objectives. It is more about the OBJ 5 around pollution prevention. Driving down the credits to the ground improvement context, we also considered applicable those credits where the construction methods could impact the stakeholders' quality of life, particularly the credits from QL1.3 to QL1.5.

Regarding the 11 credits of the category of Leadership, the connection between EU and Envision is focused on the synergies for the reuse of by-products, both to match the objectives of circular economy and pollution prevention. Therefore, we decided to significantly reduce the credits applicable to the ground improvement cases mainly because of their more ‘general’ relevance. We kept those related to the life cycle and sustainability management because they are essential to the case studies we will analyze.

Being the EU policy focused on the ecological transition of the economy, the 13 credits of the Resource Allocation category are among the most deeply connected with the taxonomy objectives. Following the same method used for the other categories, the applicable identified credits relate to green procurement practices, recycled material, and waste management in the construction site. Similarly, it goes for construction energy consumption, renewable energy use, and, most importantly, water use and management onsite during construction.

The category of Natural World, with its 13 credits, is very much related to the project's final scope. The ground treatment is a ‘special’ part of it. Therefore, many credits have been considered not applicable: we decided to keep only those related to stormwater and the protection of soil health because they are very relevant to geotechnics.

Finally, the last category, Climate and Resilience, with 9 credits, where the connection between EU and Envision is very much related to greenhouse emissions.

TABLE 1. REDUCED FRAME ENVISION VS. DNSH FOR GROUND IMPROVEMENT TECHNIQUES. THE LETTERS IN THE LAST SIX COLUMNS CORRESPOND TO SUBSET REQUIREMENTS OF THE DNSH CRITERIA OF THE EU REGULATION

Envision category	**Envision credit**	**Maximum Points Available**	**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**
Quality of life: Wellbeing	QL1.4 Minimize Noise & Vibration	12	–	–	–	–	–	–
Quality of life: Wellbeing	QL1.6 Minimize Construction Impacts	8	–	–	–	–	–	–
Leadership: Collaboration	LD1.4 Pursue Byproduct Synergies	18	–	–	–	a, c, e, f, g, h, j, k	a, c, e, f, g, h, j, k	–
Leadership: Economy	LD3.3 Conduct a Life-Cycle Economic Evaluation	14	–	–	–	–	–	–
Resource allocation: Materials	RA1.1 Support Sustainable Procurement Practices	12	–	–	–	d	d	d
Resource allocation: Materials	RA1.2 Use Recycled Materials	16	d	–	–	c, e, g	–	–
Resource allocation: Materials	RA1.4 Reduce Construction Waste	16	c	–	–	f, g, h, j, k	–	–
Resource allocation: Energy	RA2.2 Reduce Construction Energy Consumption	12	c	–	–	–	–	–
Resource allocation: Energy	RA2.3 Use Renewable Energy	24	a	–	–	–	–	–
Resource allocation: water	RA3.3 Reduce Construction Water Consumption	8	-	–	b, c	–	–	–
Natural world: Conservation	NW2.4 Protect Surface & Groundwater Quality	20	-	–	d	–	a	a
Natural world: Ecology	NW3.5 Protect Soil Health	8	f	–	–	–	a	b, d
Climate and resilience: Emissions	CR1.1 Reduce Net Embodied Carbon	20	d	–	–	c, d	–	–
Climate and resilience: Emissions	CR1.2 Reduce Greenhouse Gas Emissions	26	e, f	–	–	–	–	–
Climate and resilience: Emissions	CR1.3 Reduce Air Pollutant Emissions	18	–	–	–	–	a, b	–
	Maximum achievable rating	232						

The table above shows the correlation between the selected Envision indicators and the corresponding EU objectives (in the text of the EU regulation, each target is organized in sub-targets labeled with letters). As can be seen, almost all of the targets are intersected by at least one or more than one Envision indicator.

The same procedure can be used for any construction process and forces the decision maker to consider the broader picture when assessing sustainability, even in the case of a particular process, as we did for ground improvement techniques.

At the bottom line of the table above, the scores for Envision and (the corresponding) DNSH are summarized.

2.2. Phase two: the need for an LCA cradle-to-gate analysis

The simplified assessment tool that we just proposed is needed in the first step of our methodology and, as said, creates the framing for the specific construction case. When it comes to defining the ratings for each indicator, following the Envision protocol rules, the decision maker has to move from a qualitative to a quantitative evaluation of the optimal strategies. Within this transition, the LCA approach is necessary to support the decision with a quantitative cradle-to-gate life cycle span specifically addressed to the construction process site (also called cradle-to-site).

Setting the boundary of an LCA to the site construction process can be relevant depending on the process. Even if the materials and products used may have central relevance in terms of impact, when it comes to construction processes, the implementation at the site can create alternatives and make a difference towards the environmental burden, like the case of ground improvement techniques.

A product's overall sustainability based on an LCA study is often connected to the EU ecolabelling type III, referred to as the Environmental Product Declaration (EPD) [26]. However, this approach is controversial to a certain extent because it often does not accurately measure the overall sustainability, just stopping at the '*gate*' of the site work.

A complete life cycle analysis for the whole project requires significant modeling and multidisciplinary design choices that make the full LCA a challenging tool for sustainable decisions for large construction and infrastructural processes. An LCA analysis focused on a cradle-to-site phase that isolates a specific construction process can help to fine-tune technologies, materials, and site work choices that are still relevant to the overall sustainability performance of the whole project and can support the transformation of a specific slot of the supply chain of a large construction project.

This is why a cradle-to-gate LCA analysis at the site is proposed as the second step of our methodology. It can support the ground to the Envision indicators' rating and, finally, being connected through the framework to the EU taxonomy, giving quantitative feedback to the EU Regulation seeks.

2.3. Phase Three: Assessment of Fine Tunings

Once the LCA analysis is completed, a final assessment revision must be made to move further to the final evaluation.

In the next paragraphs, we follow the three steps for the pilot case of a ground improvement through permeation grouting in an open-air excavation below groundwater for the case of the Milan area.

The following figure represents a graphical synthesis of the proposed methodology.

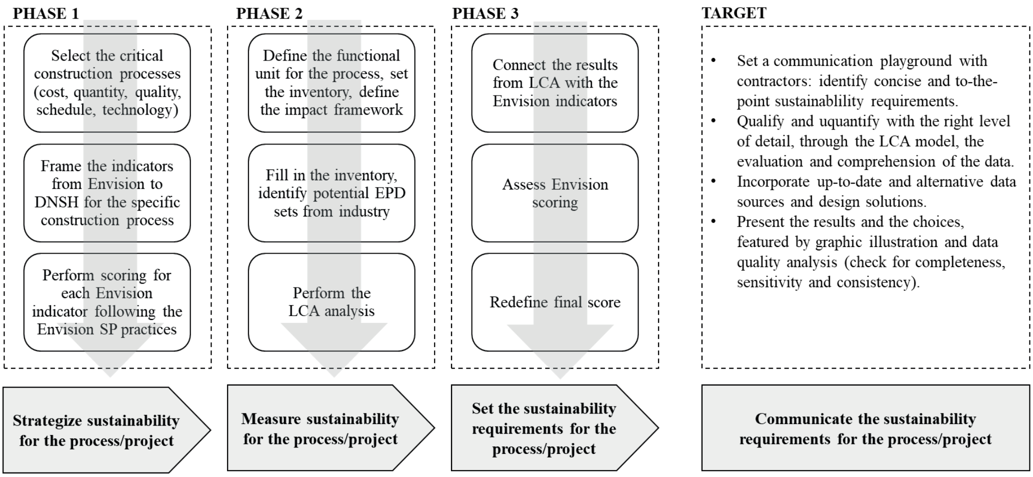

Fig. 1. The Three Phases Method.

3. A CASE STUDY FOR GROUND IMPROVEMENT TECHNIQUES

As a case for applying the proposed methodology to the soil treatment systems exposed in the previous chapter, a hypothetical excavation site in the municipality of Rozzano was selected (the case study is implemented in detail in [5]. The choice of the location is dictated by the knowledge of the area deriving from our previous experiences, which provided the geological and hydrogeological information needed.

The excavation site is assumed to have the following characteristics: square shape with sides of 10 meters each and depth of 5 meters.

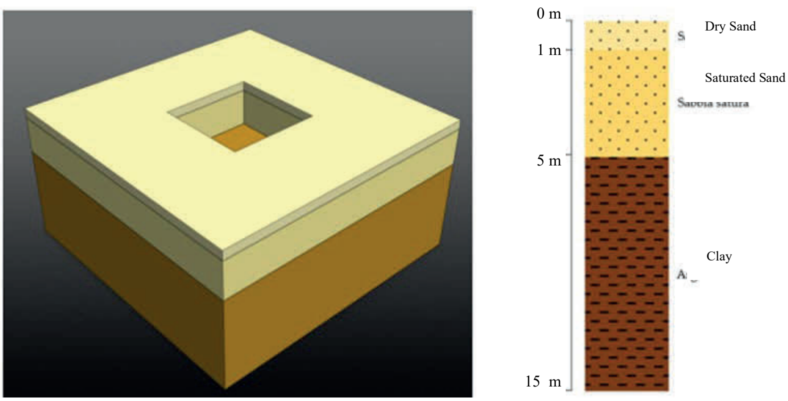

Fig. 2. The open-air excavation for the case study [5].

Depending on the site-specific characteristics, all the geotechnical and behavioral parameters of the treated soils and the geomaterials used were calculated to model a permeation injection intervention (permeation grouting).

Ground treatment is guaranteed by placing 82 columnar elements in the ground (valved pipes). Columns make the geotechnical solution of treated soil with a radius of 75 cm and a plan distance of 1.2 m for a volume of treated soil equal to 472 m^3 derived from a ground thickness of 2.50 m.

3.1. Phase One: Qualitative Application and Sustainability Rating

As a first step, we apply the framework combining Envision and DNSH to the case study, as developed above.

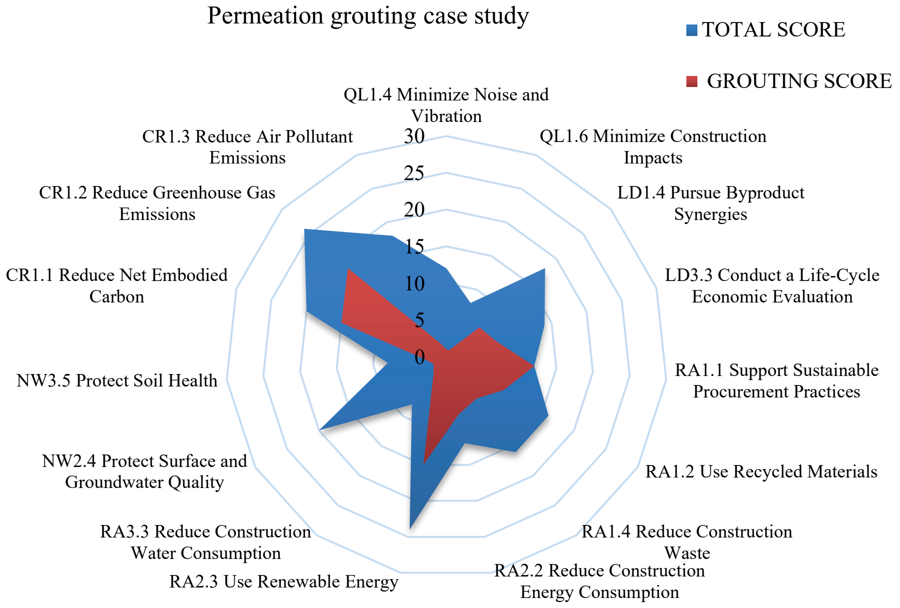

Fig. 3. The open-air excavation for the case study [5].

In the design of the case study, those indicators that depend on the community and landscape context will be set to the minimum score allowed by Envision. Those that can be deepened through the LCA cradle-to-site analysis of the process will be appointed depending on the nature and limitations of the technologies adopted and the expected results from the LCA analysis. These values will be refined in phase three after the numerical analysis. Finally, the radar graph illustrates the scores evaluated and compared with the maximum achievable values of the framework.

3.2. Phase Two of the Assessment: Getting Quantitative

The LCA analyses for the case study are performed with *Simapro* [27]. *SimaPro* is a commercial software for carrying out life cycle analysis. This tool was chosen because it is a well-recognized reference by industry professionals. We used *Ecoinvent 3.6* as the inventory for the project (allocation, cut-off by classification – system process). Finally, the Life Cycle Impact assessment method adopted in the analyses is the Environmental Footprint (EF) method 3.0, originated by an initiative of the European Commission [5].

The permeation grouting treatment process is split into subprocesses: grout mix preparation on-site, injection, drilling and positioning of the TAMs, and on-site transportation.

The relevance of on-site grout mix preparation is around 83 %, and drilling is 14 % of the overall single-point score.

3.3. Phase Three of the Assessment: Putting All Together and Reviewing the Envision Framework Results

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 assigned. Table 2 summarizes the ratings also for the DNSH criteria.

TABLE 2. ENVISION VS DNSH REVISED RATINGS [5]

	Maximum ENVISION Points Available	Minimum ENVISION Points Available	Score Permeation grouting		Scored EU environmental targets Permeation Grouting: Climate Change mitigation OBJ 1	Climate Change adaptation OBJ 2	Sustainable use of water and marine	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 %						

4. DISCUSSION AND RECOMMENDATIONS

The qualitative aspect of the proposed method, which focuses on the application of the Envision protocol to a specific construction process within the proposed case study (i.e., improvement of the soil in the Milan area surrounding an open-air excavation) forces the stakeholders to expand their design targets to the full range of the economic, environmental, and social goals. Thus, specific attention is addressed to indicators like noise and vibration, recycled materials use, waste reuse, water conservation, energy consumption, resource scarcity, economic value, sustainable procurement practices, construction impacts on communities, and air quality. This expanded vision does not consider only the carbon footprint (i.e., greenhouse emissions as CO_2 equivalent). The proposed method is used to broaden the range of sustainability indicators further. The fundamental principle is that the metrics to set the indicator score are shared and stated in a recognized third-party protocol (in this case, Envision and the Institute for Sustainable Infrastructure [15]).

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 fine-tuning of the process and optimizes the environmental performances considering the social and economic components embedded in the protocol application. This can genuinely identify critical and hot spots that can stimulate the industry in the form of transparent indicators/requirements available for the procurement criteria of contractors and owners. LCA has this power when it is focused on the process: it can become the language through which owners and the construction industry can make measurable and suitable proposals.

Two main limitations can be identified so far in the method.

The first one, which is also a potential strength, is about the limitation of the boundary of the analysis to the construction site. We limited the analysis to the cradle-to-gate (or the cradle-to-site) mainly because, in the case of civil infrastructure, the more significant part of the impact happens during the phases of construction (and of production of the construction 'ingredients'). In contrast, the operational phase tends to be focused on the maintenance in itself or on the consumption of energy (that can be easily identified and measured with other methods). This limitation can be solved in two ways (that will be the subject of further research from our side): expand the limits of the analysis to further steps like use and maintenance (B1 and B2 in the EN 15978:2011 nomenclature) or create dimensionless indicators that can embed these phases [28].

The second limitation is the area of more significant research from our side at this moment. LCA is typically based on 'standardized' data from international and recognized databases that tend to be too far from 'reality' regarding construction sites. This is unavoidable when the analysis through LCA spans the entire life of infrastructure: the number of products and processes involved and related data is so large that simplification and average statistics become a must. However, the industry needs more. If we want to engage the procurement office of a contractor, we need to dig more and stay closer to the working site reality. This is why we chose to focus on construction processes. A source of more specific data, considered the current state of the construction industry, is there to be used: it is the Environmental Product Declaration (EPD) system. The information from the EPD can be used to feed the LCA and fine-tune the analysis comparing different 'real' ingredients to the construction process. Once this is done, the analyst could compare products that enhanced their green supply chain and increase the impact score and the Envision evaluation. This can be done for concrete, asphalt, and reinforcement for all the leading players of an infrastructure impact. Our current research involves Industry (through producer associations, owners, and contractors), Academia (for methods), and Software Producers (to facilitate access to EPD).

Keeping the focus on geotechnics, this approach can be applied to the full range of ground improvement techniques comparing permeation grouting, jet grouting (with mono- and bi-fluid systems), ground freezing (with brine or nitrogen).

5. CONCLUSIONS

This paper develops a three-phase method that combines a sustainability assessment framing through indicators with LCA analysis focused on crucial construction processes to assist stakeholders in the construction industry in making decisions. The indicators from the Envision framework have been connected to the DNSH criteria to comply with the requirements of the EU regulation on green finance within the proposed methodology.

This approach can be critical to two further developments: on the one side, it stimulates the construction supply chain to invest in EPD certificates and green solutions that can easily be read and evaluated by our method and that could transparently and quantitatively show their sustainability characteristics; on the other side, a process based LCA can stimulate straightforward methodology fine-tuning and alternatives evaluation through sustainability lenses and metrics. This represents a reliable opportunity to sustain a green supply chain in the construction ecosystem.

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