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Advances in assessing the sustainability of geotechnical ground improvement processes

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Summary

1 Introduction: Sustainability and Geotechnics

1.1 The context

The process of urbanization on Earth is seeing a rapid acceleration. The ongoing megatrend, in conjunction with the driving forces of population growth and limited resources, necessitates a constant demand for new infrastructure and housing, as well as the expansion and refurbishment of existing assets. Consequently, this frequently results in the emergence of underground urban planning solutions. It is an undeniable reality that a diverse array of flows, encompassing individuals, commodities, water, energy, waste, and more, are being accommodated by underground infrastructures in contemporary times. The building methods employed in these infrastructures are progressively advancing in terms of sophistication and efficiency. However, there has yet to be a matching development in terms of sustainability and the mitigation of environmental damage. The available instruments for conducting comprehensive assessments of the sustainability of these approaches, encompassing social, environmental, and economic dimensions, are now somewhat restricted. This is mostly due to the nascent nature of the subterranean 'engineering ecosystem', which is predominantly tailored to address specific requirements and can be considered archetypal in nature.

Simultaneously, stakeholders within the construction ecosystem are increasingly encountering green procurement systems, such as the Green Procurement System endorsed by the European Union (EU) as outlined in COM [2008]. These systems encourage the sector to disclose operational decisions (technological, productive, organizational) that aim to mitigate environmental effects and validate the presence of a corporate strategy focused on sustainability.

The objective of this study is to establish a straightforward approach for assessing the sustainability and environmental (as well as social) consequences of ground improvement and geotechnical projects. This evaluation will be conducted in accordance with the European Union's Green Deal, internationally recognized sustainability rating systems, and quantitative analytical techniques.

The European Union's industrial plan, released in May 2021, has designated the construction ecosystem as one of the 14 key ecosystems within Europe. As a result, the European Commission is closely monitoring this sector. The aforementioned industry sustains a workforce of 25 million individuals and encompasses a total of 5.3 million enterprises, with small and medium-sized enterprises (SMEs) constituting 99.9% of this figure. In addition, it is noteworthy that the European building goods industry accounts for over 10% of the added value within the European Union. This sector encompasses a significant number of firms, around 430,000, which collectively generate an annual turnover of 800 billion euros and contribute a gross added value of 240 billion euros. Over the last three years, several building materials, including those made from aluminum, copper, steel, and wood, have seen substantial swings in supply and demand, leading to price volatility. These fluctuations may be attributed to robust demand, global extraction dynamics, and elevated transportation expenses. In addition, it is worth noting that some building items, like steel, glass, and aluminum, are characterized by a high energy consumption throughout their production process. This renders them particularly vulnerable to the impacts of the ongoing energy crisis [EPRS, 2022].

Infrastructures and buildings are often considered a relevant part of sustainable development because of their crucial role in society, the economy and the environment:

- The construction industry is responsible for about 10% of the global Gross Domestic Product (GDP) and employs 100 million people [Benoit et al., 2010].
- It consumes a large number of resources: 33% of the global energy consumption, 40% of the raw material consumption, contributing to 40% of the global solid waste generation [Choi, 2019].
- Concrete production industry is responsible for about 7% of the global emissions, the iron and steel industries come right after [Zamagni et al., 2013].

- Material extraction and manufacturing account for about 90% of the total environ-mental impact of a residential building, while resource extraction and manufacturing contribute about 60% of the construction costs [Benoit et al., 2010].

The building sector annually consumes a staggering 1.6 billion tons of materials. The manufacturing process of these materials results in the release of 250 million tonnes of carbon dioxide equivalent (CO2e). In the context of constructing a structure, the construction phase alone accounts for around 50% of the cumulative emissions during its lifespan. In the context of a thesis on infrastructure, it is anticipated that there will be a need to reference data pertaining to a specific building case. It is evident that the realm of infrastructures has exhibited a delay, particularly in terms of sustainability, in comparison to the field of construction. Consequently, the available environmental data within the sector primarily pertains to the latter. In order to provide a comprehensive overview, it is important to note that building and demolition waste holds a prominent position as the primary waste stream within the European Union, accounting for more than one-third of the total trash generated. In contrast, there is considerable variation in reuse and recycling rates across the European Union. Despite the Waste Framework Directive, 2008/98/EC, setting a recovery target of 70% by weight for this waste stream by 2020, the predominant methods of recovery continue to be storage operations in specialized or non-specialized landfills, as well as the utilization of low technological quality approaches such as the reuse of recycled aggregates in road foundations and conglomerates.

In order to ensure the sustainability of the construction sector, a framework of this nature necessitates a fundamental intervention within the value chain. This intervention is crucial in response to the more demanding and ambitious targets set by the European Commission and member nations. Life cycle thinking, along with its associated techniques such as life cycle assessment, has significant importance within this setting. These tools enable the quantitative assessment of the sustainability performance of the items and processes under analysis. [Hojjati et al., 2017]

1.2 Looking for the System

Sustainable development saw its formal definition in the Brundtland report of 1987 and focuses our attention on balancing the needs of present and future generations [Paulsen, 2001]. The growth in our awareness of sustainability is also a consequence of the increasingly evident climate change, the scarcity of resources, free territory, and energy.

The effects that the uncontrolled exploitation of the planet generates have an impact on the entire ecosystem and, as such, cannot be schematized with traditional linear analyses. A reaction aimed at minimizing a particular impact leads to the involuntary maximization of another, or focusing on a particular phase of use does not allow us to see the feedback on the others. This is why, when considering the effects of the production or construction of an artifact, it is necessary to put ourselves in a position to have the entire picture of its entire life cycle in front of us. The phases of the life cycle of a product or technological process can be reduced to (a) how the materials that constitute it are obtained, (b) how the parts are made, (c) how it is built, (d) how you use and manage it, (e) how you keep it in good condition, (f) how you destroy/demolish it and (g) how you get rid of what's left of it, a cradle-to-grave view, as they say [Simonen, 2014]. To prevent "burden shifting" (i.e., the movement of impacts along the same value chain or from one chain to another), it is necessary to consider all these moments of the life cycle. As we have said, concentrating the actions on one could unintentionally, increase the impact of one of the others [Hauschild et al., 2017].

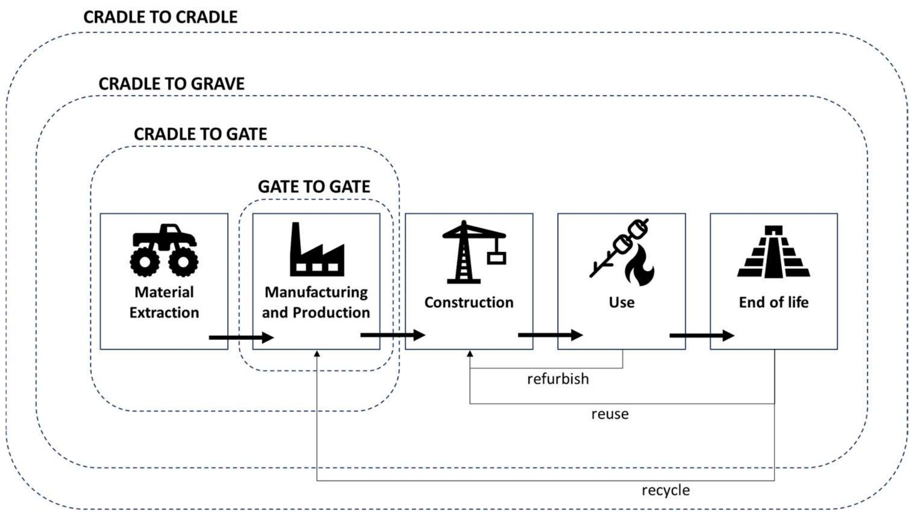


Fig. 1-1, The cradle to grave cycle.

The field of life cycle assessment (LCA) addresses the necessity of quantifying the whole environmental impact of products and activities. The technique and applicability of Life Cycle Assessment (LCA) have undergone substantial evolution since its first development in the 1960s. In the context of construction and infrastructure, the utilization of Life Cycle Assessment (LCA) can provide valuable insights for engineers, designers, and producers. LCA enables these stakeholders to enhance their decision-making processes, assess the environmental impact of materials, construction components, and processes, and foster the identification of strategies and methodologies aimed at mitigating these effects [Andersson and Listén, 2014].

When we talk about the life cycle, the reference metaphors are always, and deliberately, biological and systemic [Rieckhof, 2017]: the life cycle takes into account the biological evolution of an organism or an ecosystem from when it was born (in our case, the extraction of the original materials) to when it dies (obsolescence, demolition, reuse, etc. of an infrastructure). A second metaphor arrives through the interposition of the social sciences (created by Lord Beveridge, the inventor of the concept of the Welfare State). It is that of the cradle to grave (from the cradle to the grave. It is another way of talking about life cycle, and allows a whole series of variants: (1) from cradle to cradle (From Cradle to Cradle, as the title of the famous book by William McDonough and Michael Braungart states, 2010), to refer to the adoption of circularity criteria in waste management, (2) from the cradle to the gate (from cradle to gate or from cradle to site), to refer to processes that go from the materials of origin to the 'gate' of the site of use, (3) from gate to gate or from gate to the grave, for indicate phase of the life cycle that goes from one intermediate to another or from one intermediate to the final one (from gate to gate or from gate to grave).

While LCA has predominantly been employed in the infrastructure sector to establish overarching policies and projects [Backes and Traverso, 2021], it can serve as a potent facilitator for sustainable procurement practices when accompanied by precise data on materials and technological processes. By selecting appropriate objectives such as cradle-to-gate or cradle-to-site, and utilizing specific data derived from Environmental Product Declarations, LCA enables the comparison of various material usage scenarios and the assessment of the advantages associated with adopting innovative or more sustainable construction methods.

1.3 An existing gap: the need for sustainability metrics to push ahead a green supply chain in the construction industry

An existing gap: the need for sustainability metrics to push ahead a green supply chain in the construction industry. Sustainability is a multi-dimensional concept that promotes a balanced pathway of human activities so that the natural environment is not degraded, the natural resources are not depleted beyond acceptable limits, health and happiness of the present and future generations are promoted and maintained, and the lives of other species are preserved [Basu, 2013]. There is an additional temporal dimension to sustainability because what seems sustainable today may not be considered sustainable after few years, and this plays a relevant role in the construction industry: indeed, principles and practices related to sustainable development have to be constantly evaluated and updated. At the same time, sustainability instances and issues are very often not well defined and involve complex interactions and feedback loops between the society and environment [Basu, 2013]. This contrasts with the traditional way on which engineering is based on: well-established heuristics and linear pathways towards the required solutions established by communities of specialists. A 'sustainable' approach may not be acceptable at first from an industrial or economic point of view, particularly because it is more often supported by qualitative ethical and moral statements and lacks quantitative assessments [Basu, Misra, Puppala, 2015 and Basu, Puppala and Chittori, 2013, Deamer et al., 2015].

Almeida et al. (2022) explore how Industry 4.0 and technology in general can support the development of sustainability practices in the construction sector. Fuchs et al. (2014) explore more in general how sustainability can represent a business case for industrial processes.

The figure below identifies the ideal entry point of a sustainability assessment, that must happen as early as possible in the planning and strategy-making phase of a project in order to be truly effective.

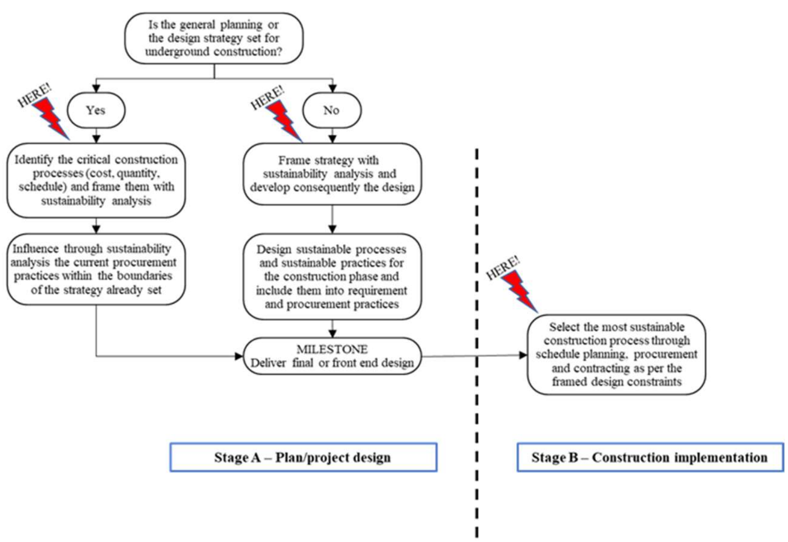


Fig. 1-2, The ideal entry points of sustainability in a construction process.

1.4 The case for Geotechnics and ground improvement techniques

In order, for geotechnical engineering, to contribute to sustainable development, the core practice must be made environment friendly and resource efficient, but mainly, geotechnics has to be able to tell, how much it does contribute. The need for a holistic complete sustainability assessment framework has been already stressed for geotechnical projects to ascertain the relative merits of different options available for a project [Basu, 2013]. According to Dam and Taylor [2011], any sustainability assessment framework should have a life cycle view of the geotechnical processes and products and should:

i. ensure societal sustainability by promoting resource budgeting and restricting the shift of the environmental burden of a particular phase to areas downstream of that phase,
ii. ensure financial health of the stakeholders, and
iii. enforce sound engineering design and maintenance.

The field of ground improvement techniques [Han, 2015], characterized by its wide range of methods and the increasing diversity of requirements and technology, is an excellent opportunity for the application of a design approach rooted on sustainability principles. One aspect pertains to the necessity of prioritizing the efficacy of processes and technologies, while the other aspect encompasses a diverse array of materials, occasionally characterized by high levels of novelty. The stakeholders involved in geotechnics, including designers, constructors, and consumers, frequently encounter the necessity for ground improvement in the presence of various contextual restrictions. These constraints encompass logistical, mechanical, scheduling, and cost-related factors. Regrettably, the allure of some choices may overshadow the consideration of environmental efficiency, hence neglecting sustainability as a viable alternative [Dalvi et al., 2021].

This thesis aims to investigate a pilot case whereby several ground improvement approaches will be employed to achieve waterproofing and stabilization of an open-air excavation situated below the water table in the vicinity of Milan. Ground improvement grouting procedures encompass the process of injecting a pumpable slurry or grout into the soil, with the aim of filling the gaps between soil particles. This procedure serves to enhance the overall strength of the soil mass and/or decrease its permeability. Permeation grouting is the term used to describe the procedure in which the spaces between soil particles are filled without causing significant displacement of the surrounding material, provided that the operating parameters are appropriately set. The composition of the fluid mixture normally consists of cement as the foundation material, along with specialized additives tailored to enhance the properties of the soil being treated. The fluid is transported into the soil using PVC valved pipes, specifically known as tubes à manchette (TAM).

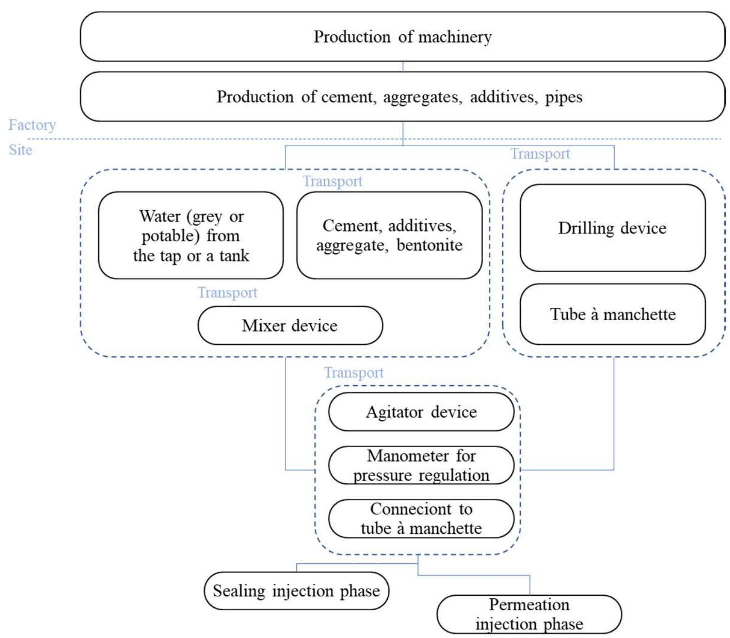


Fig. 1-3, As an example, permeation grouting construction process.

1.5 Goal of this research: a three steps method

Taking into consideration:

a) the present pressure that owners and investors are putting on the infrastructure construction sector to demonstrate tangible efforts toward sustainability, and
b) the complexity required to transparently and qualitatively comply to the EU Green Deal requirements (to get access to funding),

c) the requirement for acknowledged third-party holistic criteria that are capable of framing a project from the holistic high-level view all the way down to the individual construction process, and, lastly,
d) the requirement to quantitatively demonstrate each sustainability choice/achievement,

with this research, we suggest a three-step evaluation technique that can support decision-makers in forming sustainable choices, particularly at the building process and practice level, which is where the construction supply chain is generated. This method can help shape sustainable choices at the construction process and practice level. Being, as professionals, specialized in geotechnical engineering, the research team decided to focus on ground improvement techniques. There is full conformity with the EU taxonomy and the DNSH requirements in the propost

ed approach, which can help owners and investors enhance their efforts toward green finance.

1.6 Organization of the Thesis

After this introductory section, the subsequent chapters (2, 3, 4) will delve into the examination of sustainability standards and the regulatory arrangements established by the European Union. Chapters 5 and 6 will primarily address the establishment of a systematic linkage between the Envision protocol and the DNSH criteria. Additionally, the development of a customized set of indicators, together with their corresponding metrics, will be explored for the purpose of evaluating the sustainability of geotechnical construction processes. The utilization of this framework tool will facilitate decision makers in formulating the design and construction decisions for each operational process. This tool employs a methodology that enables a prompt demonstration of compliance with the six environmental objectives established by the European Union, as well as the extent of ambition in relation to project sustainability. Chapters 7, 8, and 9 will demonstrate the use of a specific methodology in the case study of an open-air excavation that has been subjected to five distinct ground improvement treatments. Incorporated within Chapters 10 and 11 will be the inclusion of the viewpoints pertaining to life cycle costing and social impact assessment. After establishing the sustainability objectives for building processes, the use of materials, technology, site management, waste management, reuse, recycling, and other factors will be refined through cradle-to-gate life cycle assessment (LCA) assessments. The cradle-to-gate analyses has the capacity to provide methods for enhancing the sustainability of a specific process, as measured by its effect, without excessively broadening the scope of the life cycle assessment (LCA) study, which might impede practical implementation. The application of Life Cycle Assessment (LCA) will be demonstrated in the aforementioned case study, whereby ground improvement methods, namely permeation grouting, are employed and evaluated. The findings are deliberated upon in chapters 12 and 13, examining the many viewpoints of geotechnics and the environment. Chapter 14 serves as the concluding section for the thesis. Following the inclusion of the bibliography and summaries, the appendix will delve into the examination of the Environmental Product Declaration (chapter 17) and Green Procurement (chapter 18).

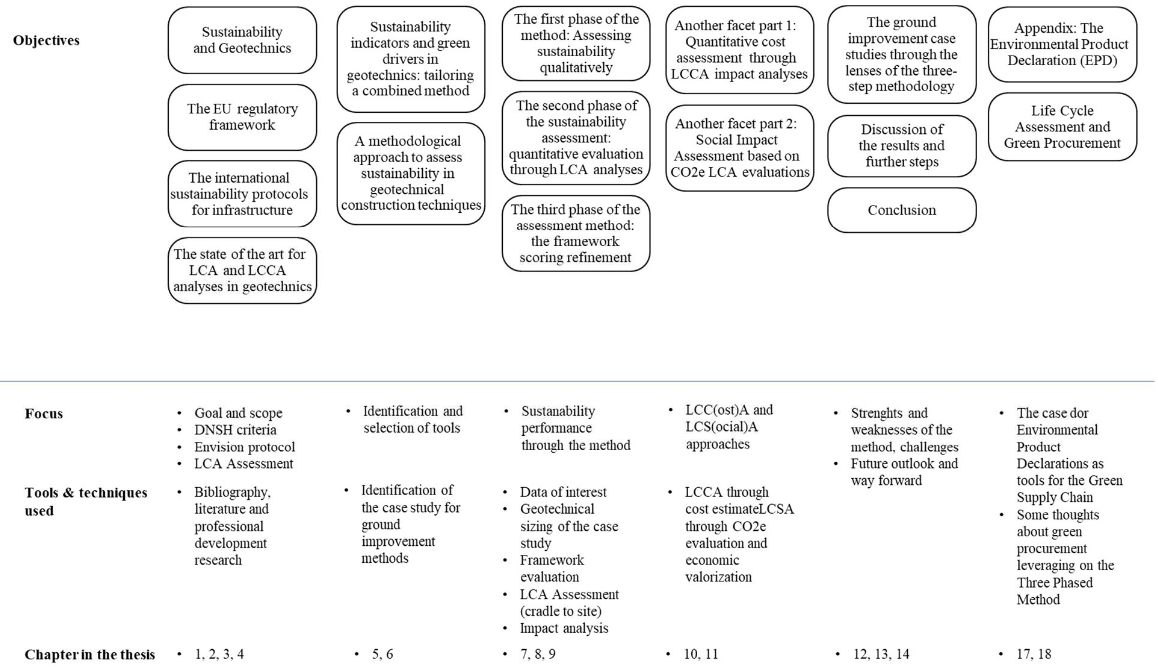


Fig. 1-4, The structure of the thesis.

2 The EU regulatory framework as a point of reference

To mitigate climate-driven risks and their impact on assets and financial institutions, global efforts from various stakeholders to foster sustainable development have resulted in the 2015 Paris Climate Agreement, a legally binding global climate agreement which emphasizes the urge to channel financial flows towards climate-resilient development and the United Nations 2030 Agenda for Sustainable Development, which sets seventeen Sustainable Development Goals (SDGs) tied to environmental, social and governance (ESG) assumptions and requirements [Meneghini, 2022]. In complete accordance with a 'follow the money' rule, this agreement actively included into the sustainability debate investors, clients, constructors, designers and forced them to develop explicit sustainability targets to get access to public green funding.

In December 2019, the European Commission introduced the European Green Deal, an extensive legislative and regulatory initiative designed to address climate change and various environmental concerns. The EU Green Deal outlines a novel growth strategy with the objective of transitioning the European Union into a resource-efficient and competitive economy by 2050, characterized by the absence of net greenhouse gas emissions. Additionally, the plan aims to achieve a reduction of 50/55% in emissions by 2030, positioning Europe as the pioneering climate-neutral continent. The achievement of this objective necessitates a substantial investment turnaround in the order of hundreds of billions of dollars into the foreseeable future. Consequently, it is imperative to establish a robust legislative and regulatory framework that supports sustainable funding.

In pursuit of this objective, the European Union Commission established the High-Level Expert Group on Sustainable Finance (HLEG) in 2016. The primary task assigned to this group was to formulate a roadmap for sustainable finance inside the EU. The overarching aim of this roadmap was to harness the allocative function of financial markets in order to establish the most sustainable financial system globally. The final report of the High-Level Expert Group (HLEG) was published in 2018, whereby eight important suggestions were outlined. The foremost proposal pertained to the creation of a unified sustainability taxonomy framework for Europe. The aforementioned widely used "green" categorization system offers transparency and serves as a reference for market players in determining whether investments and financial goods align with the European Union's sustainability goals. This system aims to provide consistency across various standards and products, hence promoting economic development. The applicability of the EU Green Taxonomy extends to several asset categories and forms of capital allocation, necessitating alignment with the environmental public policy objectives of Europe. The Regulation (EU) 2020/852, titled "on the establishment of a framework to facilitate investment and amending Regulation (EU) 2019/2088", was enacted by the European Parliament and the Council in June 2020. It came into effect in July 2020.

The Regulation serves as the legal foundation for the European Union's Green Taxonomy framework. Its objective is to define the criteria that determine whether an economic activity meets the standards of environmental sustainability. This is done to assess the level of environmental sustainability associated with an investment. The EU Taxonomy serves as a legislative instrument aimed at encouraging investors to actively engage in the transition towards sustainable finance. Its primary objective is to provide a clear framework for defining the criteria that the European Union (EU) deems as environmentally sustainable, therefore guiding investors in making well-informed decisions on their investments. The primary justification for this approach is the necessity of providing the financial sector with explicit instructions about the categorization of environmentally sustainable activities. This is crucial in order to direct capital towards the economic and social transformation required for the establishment of a climate-resilient and ecologically neutral economy. This development is expected to facilitate the growth of cross-border sustainable investments inside the European Union [Meneghini, 2022].

To trace the contours of what is environmentally sustainable, article 9 of the Taxonomy Regulation lays out a list of six environmental objectives that represent the basis of the Technical Screening Criteria (TSC)[1]:

1. 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.
2. Climate change adaptation, i.e. the process of adjustment to actual or expected climate change and its impacts.
3. Sustainable use and protection of water and marine resources;
4. Transition to a circular economy.
5. Pollution prevention and control.
6. Protection and restoration of biodiversity and ecosystems.

Considering the above, under article 3 an economic activity shall qualify as environmentally sustainable where it meets - cumulatively - the four following conditions:

1. It contributes substantially to at least one environmental objective.
2. It does no significant harm (DNSH) any other environmental objective.
3. It complies with minimum social safeguards defined on a local national basis.
4. It complies with applicable technical screening criteria defined on a local national basis.

The EU taxonomy framework provides the construction industry with a general criterion for assessing sustainability, that is a precondition to get access to funding and financial leverage. The DNSH criteria that assesses the compliance to the six environmental objectives is quickly becoming THE sustainability criterion in the construction industry at all levels and for any technology.

2.1 Condition 1: Substantial contribution to an environmental objective.

With regard to the first condition, the Taxonomy Regulation extensively lists key principles (but no detailed activities) shedding light on what "substantially contributing" to an environmental objective means. The contribution threshold is repeatedly defined as "substantial" to clarify that limited improvements to the current state of environmental performance are not sufficient, especially in view of the colossal investment efforts required to advance the transition of the EU economy towards sustainability. Similarly, activities that can have marginal, albeit positive, incremental improvements on the environment are not deemed Taxonomy-aligned.

Substantial contribution can be achieved under three scenarios:

1. when an economic activity has either a low environmental impact or can replace existing higher-impact activities;
2. when an activity has the potential to reduce adverse climate impact from other existing activities;
3. when an activity can make a positive environmental contribution.

In addition, regarding the climate change mitigation objective only, the Taxonomy Regulation recognizes so-called "transitional activities". These are activities for which no technologically and economically feasible low-carbon alternatives are yet available. They are eligible to make a substantial contribution if they support the transition to a climate-neutral economy consistent with a pathway to limit the temperature increase to 1.5° C above pre-industrial levels, provided that their greenhouse gas emission levels correspond to best

[1] The technical screening criteria are a set of rules and metrics used to evaluate whether an economic activity can be considered environmentally sustainable under the EU Taxonomy.

performance in the sector or industry, they do not hamper the development of “greener” alternatives and they do not lead to a lock-in of carbon intensive assets.

An economic activity can substantially contribute to climate change adaptation by providing adaptation solutions that alternatively reduce the risk of adverse climate impact on the activity itself or on people, nature and assets.

Substantial contribution to the transition to a circular economy may be achieved by using natural resources in production more efficiently, through an increase in durability, reusability and recyclability of products, as well as through waste generation reductions.

Any given substantial contribution to one of the environmental objectives may also be generally achieved by means of so-called “enabling activities”, which directly enables other economic activities to make a substantial contribution to one of the objectives (e.g. renewable energy manufacturing), provided that such activities do not lead to a lock-in of assets that undermine long-term environmental goals and have a substantial positive environmental impact on the basis of life-cycle considerations.

2.2 Condition 2: Do no significant harm principle.

The second cumulative criteria that an economic activity must meet is the “***do no significant harm***” (DNSH) principle, the rationale of which is for an activity falling within one of the substantial contribution categories not to qualify as environmentally sustainable if it causes more harm than benefits to an environmental.

The Taxonomy Regulation expressly lists how an economic activity may significantly harm each environmental objective, taking into account a holistic approach to the life cycle assessment (i.e. production, use and end of life) of products and services provided by each activity.

Namely, an activity shall be considered to significantly harm climate change mitigation if it leads to significant greenhouse gases emissions and to significantly harm climate change adaptation if it increases adverse climate impact on people, nature, or assets.

Significant harm to sustainable use and protection of water and marine resources is caused when an activity is detrimental to the good environmental status of bodies of waters, whereas inefficiencies in the use of material or natural resources and increases in waste generation lead to significant harm to the circular economy objective.

Finally, activities leading to an increase in pollutants emissions and causing detrimental effects to the resilience and conservation status of natural habitats and species may cause harm to the pollution prevention and control objective and to the protection and restoration of biodiversity and ecosystem objective, respectively.

TSC for DNSH to climate change mitigation and climate change adaptation were adopted in the Climate Delegate Act, together with generic DNSH guidance for the other four environmental objectives.

2.3 Condition 3: Minimum social safeguards.

The third aggregate condition for meeting the environmental sustainability requirement is for an economic activity to be compliant with minimum social safeguards as defined in article 18 of the Taxonomy Regulation. In a nutshell, these are procedures implemented by companies to ensure alignment with a set of social and governance standards related to human and labour rights.

2.4 Condition 4: Compliance with technical screening criteria.

Finally, the fourth cumulative condition is compliance with TSC (Technical Screening Criteria). Since the EU Taxonomy does not defined types of activities but rather set a conceptual framework, the Commission has so far tried to define in the Climate Delegated Act the actual “green” list of activities that can make a substantial contribution to the two climate-related environmental objectives, i.e. mitigation and adaptation. As a result, the Delegated Act contains a detailed and list of some 85 eligible activities divided according to their macro-sectors, including forestry, transport, energy, information and communication technology, waste and water, and manufacturing.

In light of the above, practically speaking any Taxonomy-user will need to cumulatively assess whether the economic activity conducted is covered by the Taxonomy and its Delegated Acts and for which environmental objective(s), whether the activity meets the substantial contribution qualitative and/or quantitative thresholds embedded in the performance requirements set out in the TSC and finally conduct due diligence to ensure compliance with the DNSH criteria and with minimum social safeguards.

Once these steps are completed, it is possible to calculate Taxonomy-alignment and display evidence of the results by means of disclosure indicators, which we shall discuss infra.

The following scheme synthetizes the whole procedure of assessing the sustainability of an economic activity.

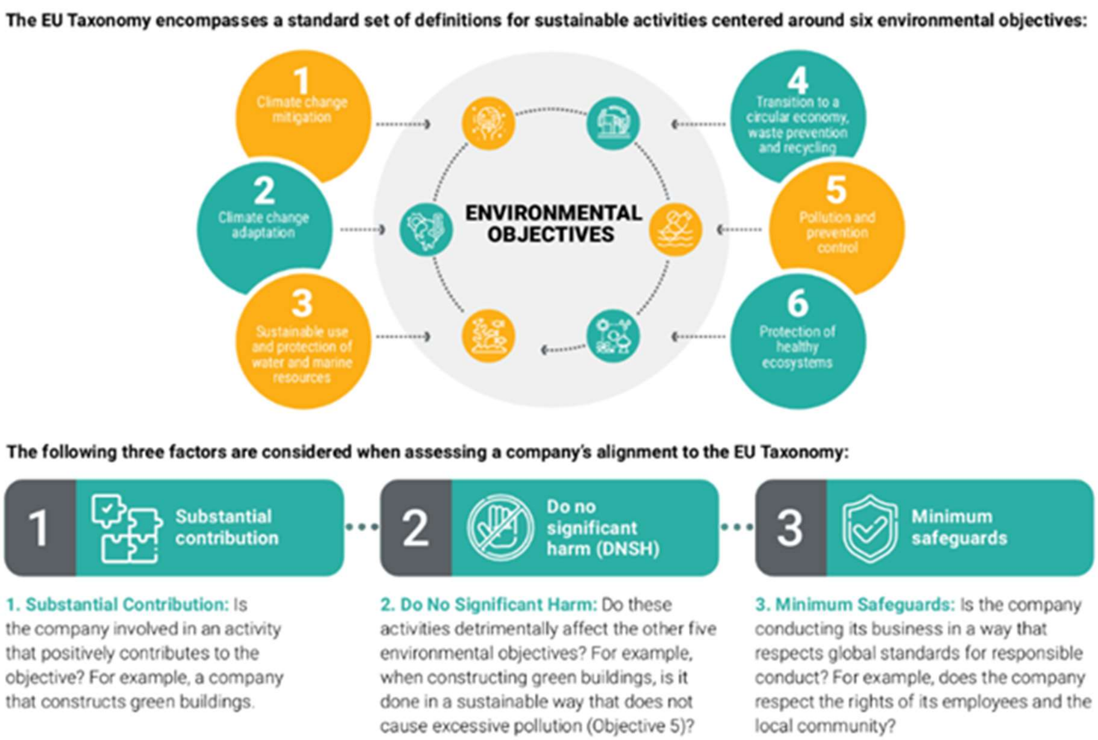


Fig. 2-1, The EU Regulation Objectives (and the Do No Significant Harm criteria) [Sustainalytics.com website].

3 The international sustainability protocols for infrastructures

3.1 The sustainability protocols and the diffusion of the culture of sustainability

The use of sustainability assessment tools in the context of the built environment began in the 1990s and 2000s, with dedicated building tools such as BREEAM (UK), LEED (USA), and Green Star (Australia and New Zealand), now definitely established and equally recognized for the substantial contribution they have given to the green building revolution [Gowri, K. et al., 2004]. At the beginning of the 2000s, as the benefits for buildings became evident, the lack of similar tools for the world of infrastructures began to be highlighted. In the UK, the civil infrastructure industry, led by the Institution of Civil Engineers, launched the CEEQUAL infrastructure assessment tool in 2003. Since CEEQUAL, specialist industry initiatives have enabled the creation of Greenroads and Envision in the United States and the Infrastructure Sustainability Tool in Australia. These four classification systems are increasingly used in the infrastructure sector, and numerous examples (and case studies) of certified projects are now available [Fenner et al., 2008, Fowler et al., 2006, Forsberg et al., 2003].

Infrastructure sustainability assessment tools work like their construction counterparts and evaluate and certify the performance of infrastructure projects and systems against various sustainability criteria (including resource use, ecology, stakeholder engagement, community impacts, climate change and resilience, land use, urban design …). These tools are generally promoted by infrastructure owners and institutional clients (such as transport agencies and territorial authorities) and applied to infrastructure asset projects by teams of specialists.

The strengths and weaknesses of assessment tools of this kind can be summarized as follows [Griffiths et al., 2018].

Strength points.

- They define a multidimensional, criteria-based approach that provides a common metric and language for all stakeholders in the infrastructure supply chain.
- They create an algorithmic mechanism for establishing a standard assessment based on third-party verifiable evidence.
- Encourage infrastructure owners, developers and project teams to strive for higher levels of sustainability performance.
- They are a concrete tool to lead/induce the adoption of sustainable practices in regulatory and planning mechanisms and in the definition of minimum standards; furthermore, they make sustainability codifiable, measurable and manageable.
- They allow clear communication of the objectives, efforts and results implemented for sustainability.
- They define a flexible framework that allows the valorization of innovation in design and construction solutions.

Areas for improvement.

- They are based on the simplification of a complex situation using a single rating "score" with a potential loss of visibility of the underlying drivers; focusing only on the final rating may not allow us to capture the entire scope of sustainable infrastructure actions, in particular social and economic issues.
- They could focus efforts on minimizing “unsustainability” rather than pushing the infrastructure construction supply chain to create something sustainable.
- For the same reason, an approach of this nature may not favor a strategy of integrating efforts, but assign 'his' limited area of action to each expert.

- It is certainly difficult to cover the entire range of infrastructure projects, which may differ in scale, character and location, with a single assessment tool.
- They could generate a tendency to "chase points" through mandatory requirements and evaluation thresholds, ending up guiding the designer or client rather than encouraging their initiative.
- They may tend to be used as a 'seal' of sustainability of a project (at its conclusion) rather than encouraging the analysis of alternatives.

The challenge of these 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) 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 of sector.

3.2 The Envision Protocol

Holistic sustainability protocols for infrastructure are slowly catching on in the global infrastructure construction industry, while they have become a methodological asset in the building industry (LEED, Green Building Council, etc.). There are different reasons for this situation: the infrastructure construction industry has been so far conservative and, as infrastructure belongs more often to public owners, safety, cost control and operational performance are still the drivers when it comes to chose and size construction processes (especially through public procurement). Some Western Countries (UK, Germany, Australia, US) started to develop dedicated frameworks after 2010 [see Holt (2011) and Holt et al. (2009), Damians et al. (2019)] and one among them, the voluntary Envision protocol developed in US by the Institute for Sustainable Infrastructures in collaboration with Harvard University [Institute for Sustainable Infrastructure, 2018], is taking over in Italy as a sector reference, with examples in various leading infrastructure systems: railway, electric grid, renewables, power generation, roads and highways, urban subways, etc..

Envision is a framework that provides the guidance needed to initiate the systemic change in the planning, design and delivery of sustainable and resilient infrastructure, as requested by the EU Green Deal. Envision is a decision-making guide, not a set of prescriptive measures and provides industry-wide sustainability metrics for all types and sizes of infrastructure to help users assess and measure the extent to which their project contributes to conditions of sustainability across the full range of social, economic, and environmental indicators. Furthermore, the Envision framework recognizes that these sustainability factors are variable across a project's life cycle. As such, Envision helps users optimize project resilience for both short-term and long-term impacts.

The framework provides a flexible system of criteria and performance objectives to aid decision makers and help project teams identify sustainable approaches during planning, design, and construction that will carry forward throughout the project's operations and maintenance and end-of-life phases. Using Envision as a guidance tool, owners, communities, designers, contractors, and other stakeholders are able to collaborate to make more informed decisions about the sustainability of infrastructure.

Community infrastructure development is subject to the resource constraints of multiple departments and agencies, each with different schedules, agendas, mandates, budget cycles, and funding sources. Ratings systems and tools intended for buildings are not designed for this context and cannot adequately assess the extensive external benefits and impacts infrastructure has on a community. Envision assesses not only individual project performance, but how well the infrastructure project contributes to the efficiency and long-term sustainability of the communities it serves.

Envision is a framework that 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 areas of human wellbeing, mobility, community development, collaboration, planning, economy, materials, energy, water, siting, conservation, ecology, emissions, and resilience.

The Envision framework is comprised of 64 sustainability indicators, called credits, that cover the full dimensions of infrastructure sustainability. Each credit in the Envision system includes an intent statement and metric, levels of achievement, a description, ways to improve performance, evaluation criteria and documentation guidance, and related Envision credits. The credits are organized into five categories and 14 subcategories by subject matter.

a. ***Quality of Life***: Wellbeing, Mobility, Community.
b. ***Leadership***: Collaboration, Planning, Economy.
c. ***Resource Allocation***: Materials, Energy, Water.
d. ***Natural World***: Siting, Conservation, Ecology.
e. ***Climate and Resilience***: Emissions, Resilience.

Every infrastructure project impacts all five Envision categories, often with complex trade-offs. For example, in an effort to avoid critical habitats, projects may have to consume more resources. Conversely, projects that reduce resource consumption may find they are also achieving the benefit of reducing harmful emissions. By grouping the credits into broader categories of impact, Envision helps users to navigate the complex trade-offs or synergies across the credits.

The Envision levels of achievement define the level and quality of project performance in each credit as follows:

- ***Improved***: Performance that is above conventional. Slightly exceeds regulatory requirements.
- ***Enhanced***: Sustainable performance that is on the right track. There are indications that superior performance is within reach.
- ***Superior***: Sustainable performance at a very high level.
- ***Conserving***: Performance that has achieved essentially zero negative impact.
- ***Restorative***: Performance that restores natural or social systems. Such performance receives the highest award possible and is celebrated as such. The Restorative level is not applicable to all performance objectives.

Not all credits have five levels of achievement. The levels are determined by the nature of the credit and the ability to make meaningful distinctions between levels. The level of achievement table clearly indicates the evaluation criteria that must be addressed for each level.

Fig. 3-1, First set of Envision credits [Institute for Sustainable Infrastructure, 2018].

Fig. 3-2, Second set of Envision credits [Institute for Sustainable Infrastructure, 2018].

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 achievement in each of the 64 credits, project teams establish how well the project addresses the full range of sustainability indicators and are challenged to pursue higher performance.

The advantage of using a frame view based on indicators is that it formulates clear and shared statements of what is achievable in terms of sustainability: a system based on absolute numerical values is unlikely to prove satisfactory [Sugade, 2019]. Differently as such, indicator systems can provide a crucial guide for decision-makers in a variety of ways, not least because they enable physical and social scientific aspects to be broken down to facilitate sustainable decision-making throughout the development process [Jefferson et al., 2007].

4 The state of the art for LCA and LCCA analyses in geotechnics

The concept of life cycle thinking, specifically in relation to cost over time, has been formulated within the context of the United States military-industrial complex. During the late 1950s, an analyst employed by the military contractor RAND introduced and subsequently applied the notion of the life cycle to inanimate objects. During the late 1960s and early 1970s, the contemporary environmental movement gained significant traction, with public sentiment, scientific advancements, and governmental involvement, particularly through the Environmental Protection Agency (EPA), serving as key pillars in its development. The heightened recognition of the numerous adverse health and environmental consequences associated with solid waste, as well as the persistent visibility of its physical presence in the environment, motivated individuals to take proactive measures. Air and water quality issues, although less conspicuous than solid waste, are of comparable importance and need enhanced governmental control for the purpose of monitoring pollution and establishing policies that ensure business is held responsible. Towards the conclusion of the decade, businesses initiated a formal process of evaluating their own involvement in the issue, linking enhancements in environmental performance to operational efficiency, and establishing the foundations of contemporary Life Cycle Assessment (LCA) models. [Guinée, 2016] [Guinée et al., 1993]

4.1 Life Cycle Thinking and Infrastructure

The life cycle concept is particularly effective for managing infrastructure assets, where assets such as roads, bridges, water, energy, and communication networks, which have a very long useful life, carry potentially significant and extensive environmental impacts. Approaching the management of an infrastructure asset from the point of view of life cycle thinking and sustainability means aiming to identify and prioritize the environmental impacts, as well as those of cost and management commitment during the entire life cycle, including construction, maintenance, and operation [Vieira, 2020].

The life cycle concept uses a systemic approach to assess environmental impacts, for example, through quantitative analysis of material and energy use, emissions, and waste production. Thanks to a vision of this nature, decision-makers in the asset management process are led to focus above all on the following points:

- Implement sustainable practices throughout all life cycle phases, including designing for sustainability, using sustainable materials and construction methodologies, and maintaining and operating practices that minimize environmental impact.
- Continuously improve operational management through extensive monitoring and reassessment, including periodic life cycle assessments and implementing best practices and emerging technologies.
- Consider the needs and expectations of stakeholders, including communities, regulators, and users, in all decision-making processes.
- Collaborate with partners and stakeholders to promote sustainability and innovation in infrastructure asset management.

As can be seen, the economic aspects (and technical, for example, durability, resilience, etc.), the environmental and social aspects (the impacts on local communities, the induced economic benefits, etc.) all contribute to the logic of the cycle of life and allow a 360° enrichment of the performance evaluation of an asset of this type [Toller and Larsson, 2017].

The specificity of the infrastructures makes the application of these principles very complex but, above all, it requires a profound knowledge of the characteristics, history, and potential of the specific asset and, as we have seen, each infrastructure network represents a 'prototype' in itself, and therefore, from the point of view of life cycle assessment, an always different and very close 'inventory' [Liljenström et al., 2013, 2019, 2021].

4.1.1 The infrastructure life cycle

Taking up a suggestive vision of the economists of the Collective for Fundamental Economics [Barbera, Negri, and Salento, 2018], the large infrastructures that serve daily life are not just tools for strengthening other economic activities, nor are they just molecular and isolated assets; large infrastructures define the spatial and temporal coordinates of our experience. They give substance to citizenship, understood as the possibility of living a free and dignified life, and are a decisive part of the fundamental economy, which is the infrastructure of daily life.

The infrastructures of Fundamental Economics arise from a political, entrepreneurial, and ethical effort that began at the end of the 19th century and continued until the early 1970s. It is an effort that begins at the municipal level and then passes into the hands of the states, at least until they can afford it. From a certain point on, it becomes transparent and is taken for granted. Infrastructures are "fundamental" (fundamental): civil life (as we conceive it) is impossible without them.

Much of Europe's infrastructure was built before 1960 and is now close to the end of its theoretical helpful life, which at the time was estimated at 30 or 50 years. In some cases, the quality of the service they provide could be more optimal, and the state of conservation is critical. Although, as highlighted by Farhani et al. (2019), the 'culture' of maintenance remains relatively weak for works that were thought of as 'substantially eternal', the regeneration of existing infrastructures requires a joint effort and enormous attention from the political, economic, and technical world. Strategic management of regenerative activities becomes essential, moving from extraordinary to ordinary maintenance based on in-depth assessments and evaluations, which must consider the needs of the operation and the need to maintain the level of service that communities require [Fregonara, 2020]. Thus, once again, life cycle thinking and assessment become essential.

Until not long ago, the economy of the construction world adopted a linear philosophy: the logical sequence of a linear economy can be summarized in the sequence of verbs: take-make-use-dispose, applied starting from raw materials.

Fig. 4-1, The linear economy of the Construction Sector.

It is an approach that aims to make the most of material resources with a short-term horizon, and which has now shown all its limits when the planet's pollution levels have begun to no longer be able to be ignored. The awareness of climate change did the rest [Bonviu, 2014]. Starting from this recognition, the concept of circular economy was born which we can define as 'self-generating economic development'. This principle assumes that:

- the development of an advanced country can take place even without giving rise to the uncontrolled exploitation of the natural and social resources of its territory and of the planet on which we live.
- The way in which decision makers must represent an infrastructure through the system that makes it possible is the logic of the life cycle, and it is the methodology that, for some years now, the European Union has been proposing us to use to change the supply chain and the resilience (also social) of the world of infrastructural construction, just as the regeneration program is being implemented.

The combination of circular economy and life cycle thinking is the basis of the criteria that inspire the European Green Deal [Dalhammar, 2015].

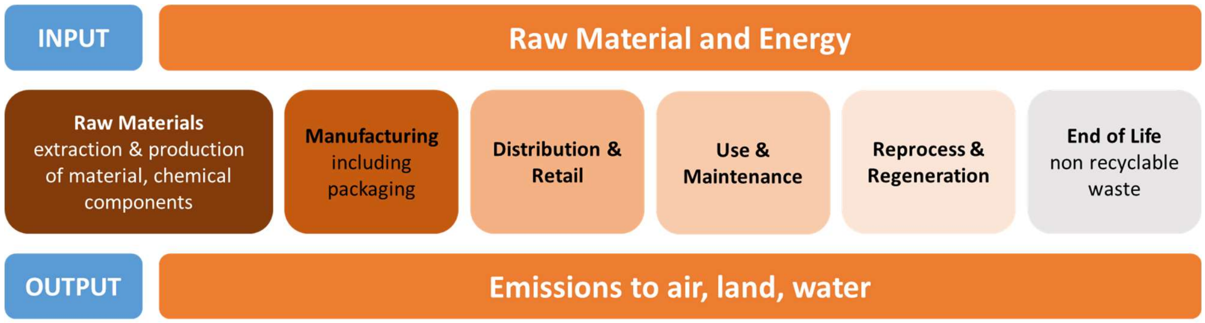


Fig. 4-2, The Life Cycle Thinking approach.

Each infrastructure has its own unique process and life cycle: an exciting way to represent it is to think of it according to the principle of the six 'r's represented in the figure, (a) rethink the material or product and its functions (re-think), (b) reduce the depletion of energy and natural resources (re-duce), (c) replace with alternative materials/products those that have harmful effects on the environment (re-place), (d) recycle the material/product and reduce waste (re-cycle), (e) reuse existing assets (re-use), (f) repair and regenerate obsolescent assets (re-pair) [Nazir, 2017].

Fig. 4-3, The 6-R approach.

It goes without saying that life cycle thinking and circularity perfectly embody the tripartite division of the concept of sustainability and allow us to comprehensively analyze all its parts: the environmental aspect, addressed with the life cycle assessment, the social aspect, addressed with the Social Life Cycle Assessment (SLCA), and the economic one, addressed with Life Cycle Costing (LCC). The key to creating sustainable infrastructure is to keep all three aspects in balance, and, for this purpose, sustainability protocols, such as Envision, become extremely useful, offering a methodological guide to the conception and construction of an infrastructure initiative that is sustainable.

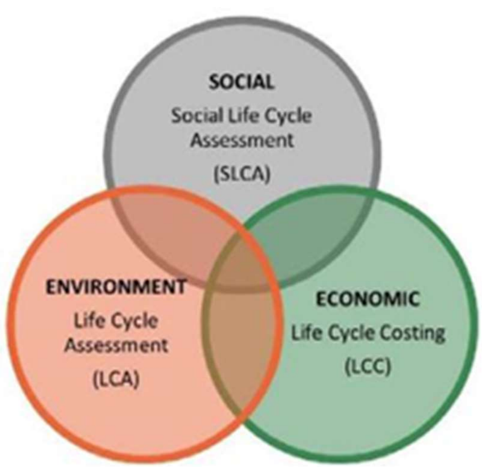


Fig. 4-4, Life Cycle Thinking, Circularity and Sustainability [Huhtala, 2015].

In short, the final objective of life cycle thinking is to improve the environmental and socioeconomic performance of the infrastructure during its entire life cycle. In particular, it seeks to help companies, clients, and professionals to be more aware of how their actions affect the environment, offering them a systemic point of view and inviting them to identify the best alternatives to reduce environmental and social consequences in the best possible economy.

The social theme in life cycle assessments is always relevant for infrastructures. They are by definition proximal, therefore rooted, territorial: they are an economy in the territory, not just an economy of the territory. This is not a possible accessory rooting but an intrinsic one: infrastructural systems and human settlements are inseparable (these are not goods and services that can be created 'far away').

4.2 Life Cycle Assessment applied to Infrastructure

We have seen how life cycle assessment is a methodological approach to analyzing systems from an environmental point of view, which examines their (environmental) implications along the entire value and production chain. It is not the only possible one; for example, environmental impact assessment and cost-benefit analysis are alternative approaches [Finneven and Moberg, 2005] [Chester et al., 2009 and 2016].

Analyzing an environmental system means framing technological (production) systems, social systems (people), and natural systems (the environment) and examining their interactions. The social component indeed 'governs' the technical one, which obtains products and services from the production system, exploits natural resources, and emits pollutants and waste into the environment. These emissions determine, in turn, changes in the ecosystem. This is why the impact analysis framework is an essential element of LCA: it is closely linked to regulatory bodies' social and political vision, focusing on technological systems within this framework. [Heijungs and Suh, 2002]

An LCA is closely connected to the discipline of industrial ecology, which, inspired by the similarity between technological systems and natural ecosystems, focuses on optimizing resource flows (materials, energy, products, services) to reduce environmental consequences. In order to achieve this, industrial ecology emphasizes the need for a systemic vision in the technological and environmental decision-making process, which is why LCA is a fundamental tool for this discipline [Hauschild et al., 2015 and 2017].

LCA allows to identify the environmental consequences of product systems and production systems, for example, by identifying the product with the most negligible impact and best environmental performance and indicating ways to improve its environmental performance. It is a methodology that allows both the analysis of the single system and the comparison of alternative systems. An LCA can detect the possible transfer of environmental loads between life cycle phases, environmental impact categories, and geographical and political areas straightforwardly and transparently [Curran, 2018].

In fact, the environmental consequences are not necessarily (or only) associated with the product itself, but a life cycle analysis allows identifying those induced by the overall system that generated it [ISO 14040, 2006]. Furthermore, unlike the environmental impact assessment, the LCA is not based on in situ measurements of environmental loads but rather on modeling potential environmental burdens deriving from the flows of materials, energy, waste, and emissions to and from the production system. In this way, the results of an LCA may not represent actual site burdens but potential regional or planetary impacts! A part of the life cycle may be well managed from an environmental point of view in one locality, a region, or a country. However, an input (or output) component may not be and contribute negatively in another region or country (the so-called 'burden shift').

The ISO 14040 (2006) and ISO 14044 (2006) standards outline the general methodological basis for an LCA analysis. This emphasis on data standardization and certification is essential because it is the only way to allow comparisons of production processes across different production chains and transnational assessments of flows and materials.

1. A life cycle analysis includes four phases:
2. Initially, the purpose and scope of the LCA, system boundaries, and functional unit are established.
3. Next, the relevant inputs and outputs of the product system are cataloged and quantified in the life cycle inventory.
4. In the third step, the environmental relevance of the production factors and products is evaluated through the evaluation of the system's impact consisting of the entire life cycle.
5. Finally, the life cycle inventory and impact assessment results are determined in relation to the purpose of the study.

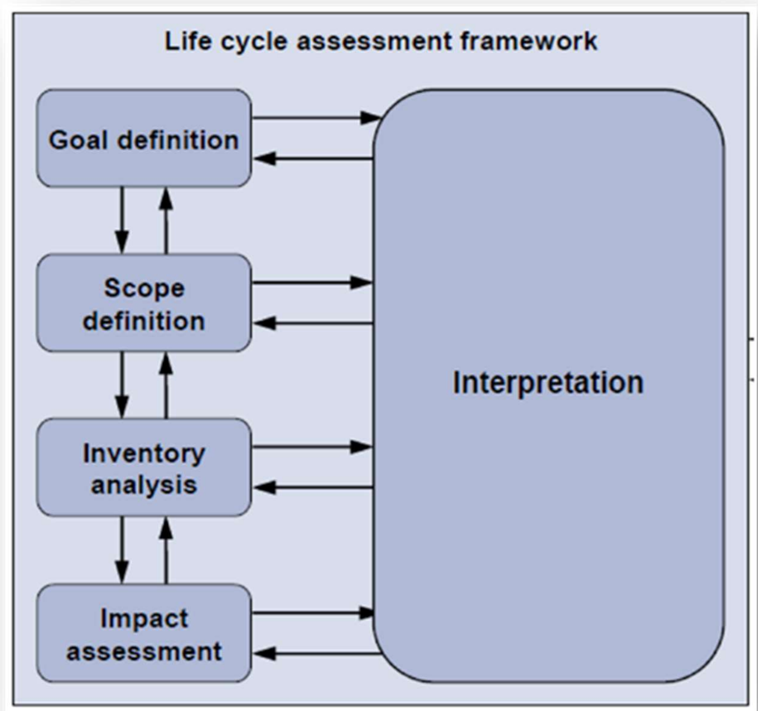


Fig. 4-5, Il Life Cycle Assessment framework [ISO 1440, 2006].

The ISO guidelines for LCA do not describe the LCA technique in detail: "there is no one way to perform LCA", and this means that there are, in fact, many application possibilities and a multitude of approaches in the world of life cycle assessment [Guinée et al., 2011].

4.3 Life Cycle Cost Analysis (LCCA)

Life Cycle Cost Analysis (LCCA) is a method to assess the monetary costs throughout a subject’s life cycle. LCCA is used to reduce the monetary costs early and during the design process. It can be used on a system level in early stages when the whole construction is studied (for example on a road section, or when comparing different alternatives in detail such as a construction part). LCCA is not as standardized as LCA and what is included can differ between different countries and different project. The following analysis procedure is used in Sweden in all large road and railway project built by the Swedish Transport Administration. LCCA is then used to minimize costs during design, procurement, construction and use. Risks and uncertainties can be included in the analysis.

LCCA should describe the investment costs and future costs such as operations, maintenance and potential external costs. The life cycle cost (LCC) is the net sum of all costs for the product during investment (planning, design, construction etc.), operation, maintenance (including replacement) and external costs (stop costs etc.) and is calculated by:

$$LCC = C_{INV} + C_{OP} + C_{MAIN} + C_{EXT}$$

where CINV is the costs in the investment stage, COP is the costs during operation, CMAIN is the costs during maintenance and CEXT is external costs. End of life costs are included if the studied subject has an end of life stage. Investment cash inflow and outflow should be discounted forward and the future cash inflow and outflow should be discounted to the cost status at the chosen baseline year. Doing this is defined as calculating its present value (PV). Net Present Value (NPV) is the sum of all PVs and can be calculated by:

$$NPV(i, N) = \sum_{t=1}^{N} \frac{R_t}{(1+i)^t}$$

where t is the time of the cash flow, i is the discount rate and Rt is the net cash flow (cash inflow – cash outflow) at time t. Other ways to calculate NPV are possible.

4.4 The three levels of application of Life Cycle Assessment in Infrastructure

4.4.1 The Network Level

Infrastructure systems are conceived (1) through three strategic decision-making levels (network, project, and process) and (2) in terms of service methods (for energy: production, transport, distribution, and use; for transport: road, rail, air or sea; for water: distribution, collection, treatment, storage; etc.). Furthermore, they are made up of a series of components, structures, artifacts, equipment, energy sources, and primary materials of origin, which are further divided into the elementary (but no less complex) processes that produce them. A mobility system, for example, is characterized by modes of transport (such as wheeled vehicles, constrained vehicles, etc.), structural systems (such as roads, trains, bridges, and tunnels), components and parts of works (such as road surfaces and railway sleepers) and materials (such as asphalt, steel and concrete).

All these elements have a life cycle that extends from the extraction of the raw materials to the end of their useful life, a term that can even be very far in time (50-100 years, but some Roman aqueducts still work today ...). The first problem in the existing literature regarding LCA is the difficulty of delineating typical horizons of space and time. Referring to a classification that derives from asset management (ISO 55000, for example), it is advantageous to identify these macro phases: conception and creation of the infrastructure, use, and maintenance of the infrastructure, demolition and/or regeneration of the infrastructure [Parra, 2020].

It is normally assumed that the production of materials (including the extraction and processing of raw materials) and the construction activity (including the transport of materials to the construction site, the use of construction machinery, and the handling of excavated materials and soil) are all part of the infrastructure construction process.

Similarly, the use of the infrastructure can be further divided into operation and maintenance. There is an ideal boundary between ordinary maintenance activities, which keep operations active, and extraordinary maintenance activities, which are a consequence of catastrophic events or interventions necessary to safeguard the usual life of the infrastructure. These activities are part of the ongoing management of the infrastructure.

We talk about regeneration when the infrastructure is re-built to relaunch its helpful life for another cycle, with real re-investment work.

The LCA focuses on the measurable environmental consequences of the materials and technologies used, highlighting the importance of reducing the environmental implications of the relevant production and management systems. Since the LCA makes environmental impacts more evident, it becomes an essential tool for establishing social indicators and creating incentives for reforming significant parts of production and, more generally, the social system. Indeed, LCA can provide information that can be used to calibrate policy and planning choices, for example, in the transport sector. [Song et al., 2020]

Planning an infrastructure system is a complicated process divided into several phases. The planning process varies from country to country. However, there are generally four primary decision levels: 1) the choice of service mode at the national level, 2) the choice of location and type of construction (e.g., bridge or tunnel) of the specific project, 3) the choice of the specific construction project and 4) the choice and influence on the supply chain involved through the procurement specifications [Miliutenkko, 2016].

The LCA can be carried out in any of these planning phases, and it relates to the purpose for which it is carried out: for example, if it becomes a tool to guide procurement, it must satisfy standards of transparency and consistency in order to provide a fair comparison of available options [Butt, Toller, and Birgisson, 2015]. Historically, the application of LCA has focused on the early stages of the decision-making process, aiming to provide systemic elements in the selection of impact scenarios. However, the application of LCA in this phase is limited by the indeterminacy of the data available at the preliminary design and feasibility level [Kluts and Miliutenko, 2012] [Butt et al., 2020]. Data would be available at later project stages. However, at that point, the potential to influence life cycle consequences is reduced [Butt, Toller, and Birgisson 2015], and LCA becomes a post-mortem exercise. However, when pushed to the more detailed and process levels, LCA can help procurement and construction decision-makers influence the supply chain sustainably.

The ideal situation would be one in which, through an LCA in the preliminary (or feasibility) phase, the general choices could be oriented (for example, identifying hot spots and top offenders), and with subsequent further LCA analyses (for example of the process) in the executive design phases and the procurement phase, it was possible to refine the choices of materials and detailed technologies. This recursion can be seen as a complication, but it brings certain benefits in terms of sustainability because it makes the most of the potential of life cycle thinking.

4.4.2 The Project Level

Even if it is rare to find an LCA analysis that openly refers to one of the three phases that we have identified [Butt, Toller, and Birgisson 2015], it is a fact, and it is a great limitation, that most of the analyzes found in the literature specialist and in the project, documents are essentially conducted 'a posteriori', i.e., once the project has been completed in a very detailed form (sometimes they accompany the 'final' Italian-style project). This is a methodological forcing that arises from the need to narrow the margin of variability of the inventory. Sometimes, the analysis becomes a kind of fulfillment following the executive planning, for example, when it is used as a support for a certification [Miliutenko 2016] [Bizjak et al. 2017], or they are purely theoretical (for example, Fridell, Stripple, and Winnes, 2016).

Indeed, this modality is often recognized as a fundamental limitation of using life cycle analysis on entire infrastructures. Furthermore, again, due to the difficulty (and complexity) of modeling the entire helpful life with adequate detail, it is not easy to find an infrastructure LCA that fully incorporates actual maintenance scenarios, which can limit its representativeness [Santero et al., 2010 ; Inym et al., 2016; Jiang and Wu, 2019].

These are reasons why a second level of application of LCA is that of the project, in which the ambition of framing different overall scenarios is abandoned to focus on the development of the specific life cycle and incorporate the most relevant scenarios of the construction, management, and maintenance.

Considering that the temporal extension of the analysis is essential and that the management criteria beyond five/ten years are difficult to predict (even if only for a question of technological evolution), the maintenance issue takes on a particularly critical role. Infrastructure maintenance has three distinct components: (1) the analysis period, which determines how many years future maintenance is accounted for; (2) the maintenance frequency, which determines the frequency with which maintenance is performed during the considered period; and (3) the effects of climate change, which are expected to influence the durability of infrastructure and, therefore, the frequency of maintenance. It is clear that only approximations are possible since the infrastructure, as we have said, 'lives' for a long time (very often longer than the technologies and decision makers who made it possible), and it is not easy to identify its 'end of life' [Saxe and Kasraian, 2020]; on the other hand, its use and functionality constantly change during its life due to wear, obsolescence, the mutation of the social and economic context in which it operates and therefore, to name one factor, the loads. Climate change, as we well understand, complicates things further [Huijbregts, 1998].

However, the more LCA is pushed to the project level (even at the cost of simplifications and typologization), the more inventories and datasets of information will be developed, gradually making the analyses more reliable generating a virtuous circle [Elorri, 2019]. A strategy that can be useful is to identify, within the useful life, those phases that are considered most relevant from an impact point of view (for materials, for technologies, for conditions of use, ...) and, programmatically, focus the analysis on them, aiming to improve sustainability performance without claiming to frame it completely. In this way, it will be possible to standardize how, for example, the construction phases, extraordinary maintenance, and, perhaps, reconstruction at the end of life are addressed. The impact on the construction value chain would be immediate and positive [Butt, Toller, and Birgisson 2015].

At the project level, the methods of conducting the LCA can become, if standardized and made transparent, an instrumental framework for the conduct of procurement policies. As many [Höjer et al., 2008] proposed, the definition of coherent and standardized scenarios by type of infrastructure could be integrated with the performance requirements of the technical infrastructure. These technological needs should be defined based on general preliminary investigations (which enrich the analysis inventory in detail) and, therefore, could also become the basis for future analyses in the same infrastructural area.

4.4.3 The Construction Process Level

The infrastructure generates a unique and complex context. It is not repeatable (for geotechnics, landscape, function ...), it has a very long useful life (sometimes more than 100 years) and goes beyond the generational gaze ..., it involves long construction times (a construction duration of five to ten years is not surprising, and note that such a duration is significantly larger than any country's current technological 'cycles' or regulatory cycles). These are just some of the reasons why the complexity of LCA analysis over the entire useful life of infrastructure is often a task that makes it challenging to define a coherent and credible data inventory. Once the problem has been framed 'from the satellite', the analysis effort must immediately concentrate on the data's realism and relevance in the critical phases (of most significant impact).

The life cycle assessment tool can be very useful, in fact, even when it is focused on a specific construction or maintenance phase, where by 'phase' we can mean either a technological phase (a particular geotechnical work, a critical construction process, etc. .) is a construction (or maintenance) phase (concrete casting, shotcrete coating, restoration of an asphalt pavement), and where the functional unit of the analysis is a 'typical' unit that represents the process [Pettinaroli, Susani et al., 2023; Susani et al., 2023].

Product	Construction process	Use	End of life	Benefits and loads beyond the system boundary
A1: Raw material supply	A4 Transport	B1 Use	C1 De-construction demolition	D Reuse-Recovery-Recycling-potential
A2 Transport	A5 Construction-installation process	B2 Maintenance	C2 Transport	
A3 Manufacturing		B3 Repair	C3 Waste processing	
		B4 Replacement	C4 Disposal	
		B5 Refurbishment		
		B6 Operational energy use		
		B7 Operational water use		

Tab. 4-1, Life cycle stages in an LCA according to the European Committee for standardization.

Of course, more importantly, when narrowing the duration and limitations of the LCA model, there is the opportunity to focus on materials and use/search for inventory information that precisely fits the "reality" of the analyzed process.

As we will see in the application cases of this document, the process approach (we could define it as 'life cycle construction process assessment') allows us to (a) isolate the materials/technologies of "maximum/greatest impact" or "maximum/greatest influence" and (b) focus on the life stages during which the most significant part of the overall impact of the infrastructure is expressed, reducing the complexity of the analysis and the influence of non-specific data.

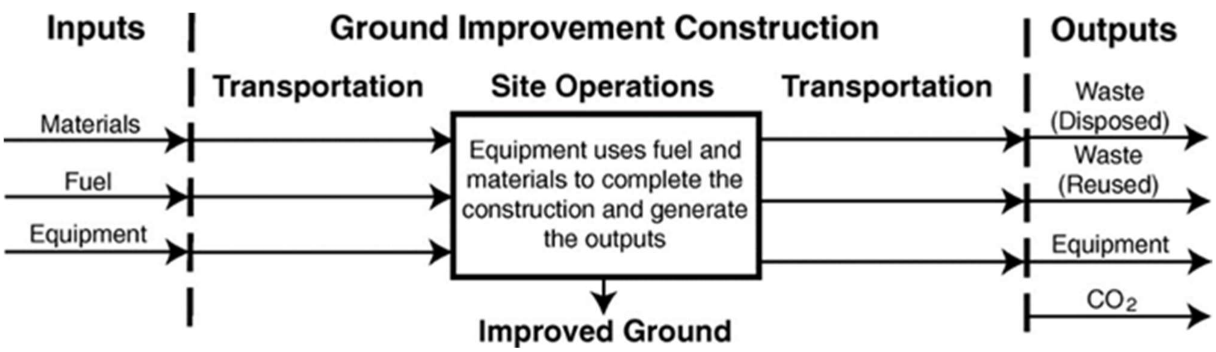


Fig. 4-6, An example of process oriented LCA approach [Raymond et al., 2021].

An LCA analysis oriented to the construction process is helpful for several purposes:

1. It allows to compare different technological alternatives and choose the least impactful one (or the one with the most significant environmental performance for a specific type of impact).
2. It allows to compare different material choice options to "measure" their respective sustainability performance using data from, for example, their EPD certificates or directly from manufacturers.

This is an advantageous approach not only during the design phase, where the sustainability objective or performance of the infrastructure is developed, but also during the procurement phase, where this type of analysis can provide valuable quantitative information to support the sustainability performance of a material or technology within a specific construction process and a specific project.

4.5 LCA and geotechnics

LCA and LCCA are sustainability assessment tools. They assess the environmental impact and the monetary cost of a product. There are also other tools that assess sustainability. What they have in common is to assess sustainability. Sustainability includes the economic, the environmental and the social part of a product or service. Sustainable development was defined by Brundtland et al. [1987] as a societal development that "meets the needs of the present without compromising the ability of future generations to meet their own needs". There are a vast variety of sustainability assessment methods available. In the following, two methods are introduced that have been used in geotechnical engineering [Lee et al., 2018] [Mickovski, 2021].

GeoSPeAR is the cited method developed by Holt et al. [2010]. It is presented as the already discussed colour-coded rose diagram that assesses the studied subject based on four main criteria: environmental, economic, societal and natural resources. Each criterion has many subcriteria and the most sustainable choices are the ones with the result closest to the centre of the diagram.

Embodied energy (EE) and gas emissions can be assessed, the process of which is a part of an LCA. Embodied energy is the sum of all the energy required during the life cycle of a product. Gas emissions can for example be the airborne emissions CO2, CH4, N2O, SOX and NOX. Inui et al. [2011] has assessed these gas emissions for four design alternatives for an embankment retaining wall system and compared the results. The most common emission to assess is CO2. Shillaber et al. [2016] developed a streamlined energy and emissions assessment model (SEEAM) used for quantifying embodied energy and CO2 emissions for ground improvement.

The quantitative multiple-criteria based assessment frameworks like Envision are mostly life cycle based tools. Looking at the infrastructure industry, life cycle costing (LCC) and life cycle assessment (LCA) have been used to assess the sustainability of pavements [Pratico et al. 2011, Zhang et al. 2008, 2011]. Pittenger [2011] developed a life-cycle based performance metric known as Green Airport Pavement Index (GAPI) for comparing the sustainability of alternative airport pavement treatments. Lee et al. [2018] combined LCA and LCC to quantitatively assess the advantage of using recycled materials in pavements. Lee et al. [2018] introduced a LCA based rating system known as Building Environmentally and Economically Sustainable Transportation - Infrastructure - Highways (BE2ST-in-Highways). Finally, Chang et al. (2018) evaluate CO2 emissions for geotechnical construction works.

Geotechnical engineers may not be that familiar with making environmental impact assessments in their daily work [Samuelsson et al., 2021], still there is a wide literature about it including general soil stabilization [da Rocha et al. 2016], foundation support [Egan and Slocombe 2010; Jefferson et al. 2010; Shillaber et al. 2017; Spaulding et al. 2008], land remediation or environmental containment [Harbottle et al. 2007; Spaulding et al. 2008] [Bardos et al., 2020], and flood protection [Shillaber et al. 2016]. As we said, the size of the investment cost is by far the most important factor when deciding if a construction project is being realized or not. But decisions made in a geotechnical engineering project affect the environmental impact and monetary cost during the structure's entire life cycle. Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) are established methods for assessing such environmental impacts and monetary cost from construction works [Gomes Correia et al., 2016]. The results can be used to make decisions to reduce the environmental impact and monetary cost in geotechnical engineering projects. However, limited research has been published in applying LCA and LCCA to geotechnical engineering. For example, Jefferis [2008] found that there was a lack of specific guidelines on how to implement sustainability in geotechnical engineering.

A life cycle assessment starts with a definition of the aim and scope of the study. Its main effort resides in the development of an inventory (LCI), in which all the significant environmental burdens from the life-time 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. The concept and working phases of LCA are described in the ISO14040 [ISO14040, 2006].

The application of LCA in civil engineering started initially as a tool for assessing solid waste management options. Because it has been thought for product development and supply chain impacts disclosure, it tends to be difficult to use in the case of civil engineering and particularly when it comes to large infrastructures. The amount of data required and the unpreparedness of the construction industry make a full LCA assessment for an infrastructure a postmortemized practice, while the tool should be a support to the decision making process. [Choudhury et al., 2018].

The concrete industry is probably the more advanced in adopting the tool, particularly because of its undeniable impact: besides giving the knowledge of products' environmental performance, LCA results are also able to support marketing or environmental labelling. For instance, the ISO14025 Type III Environmental Product Declaration (EPD), which enables the informed comparison between products that fulfil the same function, re-quires quantified environmental information based on in-dependently verified LCA results [Huang et al, 2018 and 2020].

5 Sustainability indicators and green drivers in geotechnics: tailoring a combined method

5.1 Combining sustainability indicators with the EU technical screening criteria

The EU regulation requires an explicit analysis to establish whether an economic activity could be considered to significantly harm, through the framework of the DNSH criteria and taking into account the life cycle of the products and services provided by it, including evidence from existing life-cycle assessments. When assessing an economic activity against the six targets set out above, both the environmental impact of the activity itself and the environmental impact of the products and services provided by it 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 aim of the regulator is more about forcing investors, owners, designers, and constructors to set up a sustainability strategy for their projects instead of just a general purpose or a scattered series of environmentally friendly actions. At the same time, we think that a pure compliance verification against the six targets will not support the decision makers to evolve the nature of their projects. This is why we suggest, as a first step, the adoption of a general sustainability rating protocol based on well recognized indicators, defining a thought and complete sustainable approach to the project, that could properly combine performance and economic needs with social and environmental perspectives.

The Envision protocol [Institute for Sustainable Infrastructure, 2018] is well structured, solid and allows a simple preliminary approach that is very useful in the framing phase. This can be done by selecting the applicable indicators and identifying the appropriate leverages that play the critical role in sizing the sustainability rating of the project. This phase is crucial because it allows a fine tuning of the general strategy of the project and focuses the attention of the stakeholders on the environmental and social hotspots, apart from the technical performance or the cost in itself. Without this first framing, the focus on a sustainability strategy of the project will be weak and difficult to share among the stakeholders.

The application of Envision is useful also in the light of the EU Taxonomy. Following the path traced by ICMQ [ICMQ, 2022] it is possible to identify a connection between the Envision indicators and the six targets listed in the article 3 of the cited EU Regulation. This is a simple way to check the project against the DNSH criteria, giving the chance to use the Envision analysis as a reference metric also for EU compliance. With a fundamental integration: while the DNSH assessment deals only with the environment, the Envision protocol also takes into account the economic and social aspects, thus satisfying the three ESG factors. Most of the Envision credits have a direct impact on the objectives indicated in the 2020/852 Regulation, and within the protocol there are additional credits that contribute indirectly but effectively to the achievement of the objectives themselves.

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

5.2 The guidelines from the Italian Ministry for Sustainable Infrastructure

Infrastructures constitute the backbone for the economic and social development of a territory, influencing its productivity, facilitating trade with other areas and markets, improving economic and social inclusion and ensuring its environmental and climatic sustainability. In this context, the ability of the public sector to select and evaluate the works to be financed in a systemic key is crucial to guarantee the decision-making and implementation process a reference framework that is able to combine in a synergistic way the economic, social and environmental dimensions and the aspects of technical-construction nature.

In this context, MIMS has decided to publish detailed methodological documents ("Operational Guidelines for Investments in Public Works") in order to provide the analytical reference framework for the preparation of project proposals relating to interventions in the areas of competence of the Ministry .

The Operating Guidelines, set out in separate documents for each sector of competence of the Ministry, are adopted by Decree of the Minister of Sustainable Infrastructures and Mobility and published on the institutional website and - as mentioned - will serve as a practical manual for both proposing and implementing subjects. during the preparation of feasibility projects, as for the STM called to support the competent DGs of the MIMS in evaluating the works for the purposes of their eligibility for public funding.

With D.M. of 7/12/2021, n. 496, the Ministry adopted the published first technical document dedicated to the railway sector; this document, on the other hand, is dedicated to the road sector and accurately describes the evaluation methodology to be applied to potential works financed by MIMS, through the main dimensions that characterize the sustainability of a project - economic, environmental, social and governance - as well as that the aspects of a transport nature strictly connected to the reference sector.

The Operating Guidelines, in recalling the general principles of ex-ante evaluation of investments in public works established in chapter 3 of the Guidelines (Ministerial Decree of 2017 n.300), further details the methodology of practical application.

As regards the analysis of investments in terms of environmental sustainability, this document takes as reference the Regulation (EU) 2020/852 (so-called "Taxonomy Regulation") and the Final Report of the Technical Group of Experts in charge of defining the Taxonomy to determine the substantial contribution to the environmental objectives relating to climate change in terms of mitigation and adaptation, published in March 2020 and the basis of the Delegated Regulation on climate objectives which was adopted by the EC in June 2021 (in force starting from 2022 as required by Regulation). At the same time, the Vademecum is directly inspired by the aforementioned regulation on the European Recovery and Resilience Device (RRF), as well as by the European Commission Communication 1054/2021, which details the methodology for applying the "Do not significant harm" principle (DNSH) within the RRF.

Finally, the Operating Guidelines identify a series of relevant criteria and dimensions for defining the contribution in terms of social sustainability and governance of the work, in line with European and international standards.

It will be necessary to clarify each time in which cases the interventions must be considered individually or within a broader investment program. The theme is of clear importance both for the fact that a single large project (for example a railway line) can be divided into a series of distinct interventions (the various sections or functional phases), as well as for the recurrence of large thematic containers in the investment programs, which make analysis difficult when individual interventions are small or inseparable by their very nature.

Therefore, these Operational Guidelines have the dual objective of standardizing the ex-ante evaluation methodology, in order to improve the comparability of projects, also including the non-intervention scenario, and of making the decision-making processes on evaluation transparent. of public works, also with reference to the preparation of the Plurennial Planning Document (DPP) provided for in article no. 201, paragraph n. 1 of the Legislative Decree n. 50/2016 ("Public Contracts Code") and subsequent amendments and additions.

5.3 DNSH and Recovery and Resilience Plan

The importance given to this principle is fully confirmed in the Communication from the Commission dedicated to "Technical guidelines on the application of the principle" do not cause significant damage "pursuant to the Regulation on the mechanism for recovery and resilience."

This is the Regulation establishing the recovery and resilience facility (RRF, Recovery and Resilience Facility) which establishes that no measure included in a recovery and resilience plan (RRP, Recovery and Resilience

Plan) must cause damage to environmental objectives pursuant to Article 17 of the Taxonomy Regulation, i.e. 2020/852. Pursuant to the RRF regulation, in fact, the evaluation of RRPs must ensure that each individual measure (ie each reform and each investment) included in the plan complies with the principle "do not cause significant harm" (DNSH, "do no significant harm "). The RRF Regulation also establishes that the Commission provides technical guidance on how to apply the DNSH principle in the context of the RFF. Hence the communication from the Commission.

With it, in summary, the Commission establishes that Member States must provide a DNSH assessment for each individual measure of the respective RRP and that therefore it is not possible to positively assess the RRP if one or more measures do not comply with the DNSH principle. Therefore, the DNSH assessment should not be carried out at the level of the plan or the individual components of the plan, but at the measure level. And this applies both to the measures that are considered to contribute to the green transition and to all other measures included in the RRPs.

The close correlation between the RRF Regulation and the DNSH principle is established in the explicit reference to what is contained in Article 17 of Regulation 2020/852 where it defines the "significant damage" for the six environmental objectives. For the purposes of the RRF Regulation, DNSH is to be interpreted within the meaning of Article 17 of the Taxonomy Regulation. This article defines what constitutes 'significant harm' for the six environmental objectives covered by the Taxonomy Regulation:

1. An activity is considered to do significant harm to ***climate change mitigation*** if it leads to significant greenhouse gas (GHG) emissions;
2. An activity is considered to do significant harm to ***climate change adaptation*** if it leads to an increased adverse impact of the current climate and the expected future climate, on the activity itself or on people, nature or assets6;
3. An activity is considered to do significant harm to ***the sustainable use and protection of water and marine resources*** if it is detrimental to the good status or the good ecological potential of bodies of water, including surface water and groundwater, or to the good environmental status of marine waters;
4. An activity is considered to do significant harm to the ***circular economy***, including waste prevention and recycling, if it leads to significant inefficiencies in the use of materials or in the direct or indirect use of natural resources, or if it significantly increases the generation, incineration or disposal of waste, or if the long-term disposal of waste may cause significant and long-term environmental harm;
5. An activity is considered to do significant harm to ***pollution prevention and control*** if it leads to a significant increase in emissions of pollutants into air, water or land;
6. An activity is considered to do significant harm to the ***protection and restoration of biodiversity and ecosystems*** if it is significantly detrimental to the good condition and resilience of ecosystems, or detrimental to the conservation status of habitats and species, including those of Union interest.

From 1 January 2022, the Commission Delegated Regulation EU 2021/2139 entered into force, which supplements the EU Regulation 2020/852 of the European Parliament and of the Council, establishing the technical criteria that determine the conditions for which an economic activity contributes in substantially to climate change mitigation or climate change adaptation and if it does not do significant harm to any other environmental objective.

5.4 EU Regulation 2020/852 Objectives

For the purposes of this Regulation, the following shall be environmental objectives:

1. Climate change mitigation.
2. Climate change adaptation.
3. Sustainable use and protection of water and marine resources.

4. Transition to a circular economy.
5. Pollution prevention and control.
6. Protection and restoration of biodiversity and ecosystems.

5.4.1 Objective 1: Substantial contribution to climate change mitigation

The regulation tells that an economic activity shall qualify as contributing substantially to climate change mitigation where that activity contributes substantially to the stabilization of greenhouse gas concentrations in the atmosphere at a level which prevents dangerous anthropogenic interference with the climate system consistent with the long-term temperature goal of the Paris Agreement through the avoidance or reduction of greenhouse gas emissions or the increase of greenhouse gas removals, including through process innovations or product innovations, by:

a. generating, transmitting, storing, distributing or using renewable energy in line with Directive (EU) 2018/2001, including through using innovative technology with a potential for significant future savings or through necessary reinforcement or extension of the grid;
b. improving energy efficiency, except for power generation activities as referred to in Article 19(3);
c. increasing clean or climate-neutral mobility;
d. switching to the use of sustainably sourced renewable materials;
e. increasing the use of environmentally safe carbon capture and utilisation (CCU) and carbon capture and storage (CCS) technologies that deliver a net reduction in greenhouse gas emissions;
f. strengthening land carbon sinks, including through avoiding deforestation and forest degradation, restoration of forests, sustainable management and restoration of croplands, grasslands and wetlands, afforestation, and regenerative agriculture;
g. establishing energy infrastructure required for enabling the decarbonisation of energy systems;
h. producing clean and efficient fuels from renewable or carbon-neutral sources.

5.4.2 Objective 2: Substantial contribution to climate change adaptation

An economic activity shall qualify as contributing substantially to climate change adaptation where that activity:

a. includes adaptation solutions that either substantially reduce the risk of the adverse impact of the current climate and the expected future climate on that economic activity or substantially reduce that adverse impact, without increasing the risk of an adverse impact on people, nature or assets; or
b. provides adaptation solutions that, in addition to satisfying the conditions set out in Article 16, contribute substantially to preventing or reducing the risk of the adverse impact of the current climate and the expected future climate on people, nature or assets, without increasing the risk of an adverse impact on other people, nature or assets.

5.4.3 Objective 3: Substantial contribution to the sustainable use and protection of water and marine resources

An economic activity shall qualify as contributing substantially to the sustainable use and protection of water and marine resources where that activity either contributes substantially to achieving the good status of bodies of water, including bodies of surface water and groundwater or to preventing the deterioration of bodies of water that already have good status, or contributes substantially to achieving the good environmental status of marine waters or to preventing the deterioration of marine waters that are already in good environmental status, by:

a. protecting the environment from the adverse effects of urban and industrial waste water discharges, including from contaminants of emerging concern such as pharmaceuticals and microplastics, for example by ensuring the adequate collection, treatment and discharge of urban and industrial waste waters;
b. protecting human health from the adverse impact of any contamination of water intended for human consumption by ensuring that it is free from any micro-organisms, parasites and substances that constitute a potential danger to human health as well as increasing people's access to clean drinking water;
c. improving water management and efficiency, including by protecting and enhancing the status of aquatic ecosystems, by promoting the sustainable use of water through the long-term protection of available water resources, inter alia, through measures such as water reuse, by ensuring the progressive reduction of pollutant emissions into surface water and groundwater, by contributing to mitigating the effects of floods and droughts, or through any other activity that protects or improves the qualitative and quantitative status of water bodies;
d. ensuring the sustainable use of marine ecosystem services or contributing to the good environmental status of marine waters, including by protecting, preserving or restoring the marine environment and by preventing or reducing inputs in the marine environment.

5.4.4 Objective 4: Substantial contribution to the transition to a circular economy

An economic activity shall qualify as contributing substantially to the transition to a circular economy, including waste prevention, re-use and recycling, where that activity:

a. uses natural resources, including sustainably sourced bio-based and other raw materials, in production more efficiently, including by:
    i. reducing the use of primary raw materials or increasing the use of by-products and secondary raw materials; or
    ii. resource and energy efficiency measures;
b. increases the durability, reparability, upgradability or reusability of products, in particular in designing and manufacturing activities;
c. increases the recyclability of products, including the recyclability of individual materials contained in those products, inter alia, by substitution or reduced use of products and materials that are not recyclable, in particular in designing and manufacturing activities;
d. substantially reduces the content of hazardous substances and substitutes substances of very high concern in materials and products throughout their life cycle, in line with the objectives set out in Union law, including by replacing such substances with safer alternatives and ensuring traceability;
e. prolongs the use of products, including through reuse, design for longevity, repurposing, disassembly, remanufacturing, upgrades and repair, and sharing products;
f. increases the use of secondary raw materials and their quality, including by high-quality recycling of waste;
g. prevents or reduces waste generation, including the generation of waste from the extraction of minerals and waste from the construction and demolition of buildings;
h. increases preparing for the re-use and recycling of waste;
i. increases the development of the waste management infrastructure needed for prevention, for preparing for re-use and for recycling, while ensuring that the recovered materials are recycled as high-quality secondary raw material input in production, thereby avoiding downcycling;
j. minimises the incineration of waste and avoids the disposal of waste, including landfilling, in accordance with the principles of the waste hierarchy;
k. avoids and reduces litter.

5.4.5 Objective 5: Substantial contribution to pollution prevention and control

An economic activity shall qualify as contributing substantially to pollution prevention and control where that activity contributes substantially to environmental protection from pollution by:

a. preventing or, where that is not practicable, reducing pollutant emissions into air, water or land, other than greenhouse gasses;
b. improving levels of air, water or soil quality in the areas in which the economic activity takes place whilst minimising any adverse impact on, human health and the environment or the risk thereof;
c. reventing or minimising any adverse impact on human health and the environment of the production, use or disposal of chemicals;
d. cleaning up litter and other pollution.

5.4.6 Objective 6: Substantial contribution to the protection and restoration of biodiversity and ecosystems

An economic activity shall qualify as contributing substantially to the protection and restoration of biodiversity and ecosystems where that activity contributes substantially to protecting, conserving, or restoring biodiversity or to achieving the good condition of ecosystems, or to protecting ecosystems that are already in good condition, through:

a. nature and biodiversity conservation, including achieving favourable conservation status of natural and semi-natural habitats and species, or preventing their deterioration where they already have favourable conservation status, and protecting and restoring terrestrial, marine and other aquatic ecosystems in order to improve their condition and enhance their capacity to provide ecosystem services;
b. sustainable land use and management, including adequate protection of soil biodiversity, land degradation neutrality and the remediation of contaminated sites;
c. sustainable agricultural practices, including those that contribute to enhancing biodiversity or to halting or preventing the degradation of soils and other ecosystems, deforestation and habitat loss;
d. sustainable forest management, including practices and uses of forests and forest land that contribute to enhancing biodiversity or to halting or preventing degradation of ecosystems, deforestation and habitat loss.

5.4.7 Enabling activities

An economic activity shall qualify as contributing substantially to one or more of the environmental objectives set out in Article 9 by directly enabling other activities to make a substantial contribution to one or more of those objectives, provided that such economic activity:

a. does not lead to a lock-in of assets that undermine long-term environmental goals, considering the economic lifetime of those assets; and
b. has a substantial positive environmental impact, on the basis of life-cycle considerations.

5.5 Significant harm to environmental objectives

For the purposes of point (b) of Article 3, taking into account the life cycle of the products and services provided by an economic activity, including evidence from existing life-cycle assessments, that economic activity shall be considered to significantly harm:

a. Climate change mitigation, where that activity leads to significant greenhouse gas emissions.

b. Climate change adaptation, where that activity leads to an increased adverse impact of the current climate and the expected future climate, on the activity itself or on people, nature or assets.
c. Sustainable use and protection of water and marine resources, where that activity is detrimental:
    i. to the good status or the good ecological potential of bodies of water, including surface water and groundwater; or
    ii. to the good environmental status of marine waters.
d. Circular economy, including waste prevention and recycling, where:
    i. that activity leads to significant inefficiencies in the use of materials or in the direct or indirect use of natural resources such as non-renewable energy sources, raw materials, water and land at one or more stages of the life cycle of products, including in terms of durability, reparability, upgradability, reusability or recyclability of products;
    ii. that activity leads to a significant increase in the generation, incineration or disposal of waste, with the exception of the incineration of non-recyclable hazardous waste; or
    iii. the long-term disposal of waste may cause significant and long-term harm to the environment.
e. Pollution prevention and control, where that activity leads to a significant increase in the emissions of pollutants into air, water or land, as compared with the situation before the activity started; or
f. the protection and restoration of biodiversity and ecosystems, where that activity is:
    i. significantly detrimental to the good condition and resilience of ecosystems; or
    ii. detrimental to the conservation status of habitats and species, including those of Union interest.

When assessing an economic activity against the criteria set out above, both the environmental impact of the activity itself and the environmental impact of the products and services provided by that activity throughout their life cycle shall be taken into account, in particular by considering the production, use and end of life of those products and services.

5.6 The Envision protocol in the light of measuring DNSH objectives

In this context, due to the lack of certain parameters within the guidelines, the difficulty of measuring the sustainability of infrastructures has emerged. An important help for stakeholders (professionals, companies, administrations, citizens) comes from the Envision protocol of ISI (Institute for Sustainable Infrastructure), promoted in Italy by ICMQ - Institute of certification and quality mark for construction products and services [Institute for Sustainable Infrastructure, 2018].

The Envision protocol is therefore the ideal tool for measuring the status of the six objectives DNSH and obtain a sustainability certification compliant with EU requirements.

With a fundamental integration: while the DNSH assessment deals only with the environment, the Envision protocol also takes into account the economic and social aspects, thus satisfying the three ESG factors. Envision credits allow you to assess the sustainability of infrastructures by measuring the effects they produce on every aspect of human life and the surrounding environment. In a period in which environmental certification assumes an increasingly strong role in the world of building and construction, ICMQ promotes a rating system that stimulates and enhances design and construction best practices also in the infrastructure sector.

Most of the Envision credits have a direct impact on the objectives indicated in the 2020/852 Regulation, but not only: within the protocol there are additional credits that contribute indirectly but effectively to the achievement of the objectives themselves.

The sustainability certification obtained through the compliance of the project with the requirements set by the credits of the Envision protocol therefore represents an important contribution to creating works that comply with what is indicated by the Do No Significant Harm principle.

5.7 A dedicated assessment for ground improvement projects that fosters EU DNSH criteria through Envision

One of the aims of our research is to create a state-of-the-art sustainability and resiliency assessment for ground improvement techniques, as said in the introductory part of this report. Following our professional experience and being aware of the construction industry needs, we decided to connect the ‘views’ of the EU regulation (that will set the stage for the next years) with a sustainability metric as the one that Envision declines through its protocol.

This way we will have built a tool that has a regulatory blessing (it can be used to state the compliance to the DNSH criteria) and the holistic approach of a 360° degree international protocol (that has the weakness of not being cogent).

We will make use of the guidelines produced by the Italian Institute for Sustainable Infrastructure and ICMQ (that represents the Envision organization in Italy) [ICMQ, 2022].

5.8 Correspondence between DNSH and ENVISION

As a first step we scanned the whole set of Envision credits (64 overall, divided in 5 categories, as said) in order to identify the correspondences between the Envision approach and the UE requirements.

This way, the adapted assessment that we will obtain, could be a useful tool for the industry in order to evaluate the sustainability of different ground improvement solutions, in particular, and the whole geotechnical project in itself, in general.

In the first category, quality of life, we improved the cited approach of ICMQ and then reduces the number of applicable credits to our specific cases.

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 subcase cited in the Regulation (and listed above). This way, once the score is assigned to a credit there will be a full trackability of its value under the DNSH evaluation.

			Credit Assessment Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular economy transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Quality of Life	Wellbeing	QL1.1 Improve Community Quality of Life	Not Applicable	2	26	-	-	-	-	-	-
		QL1.2 Enhance Public Health & Safety	Not Applicable	2	20	-	-	-	-	b, c, d	-
		QL1.3 Improve Construction Safety	Not Applicable	2	14	-	-	-	-	c, d	-
		QL1.4 Minimize Noise & Vibration	Assessed	1	12	-	-	-	-	-	-
		QL1.5 Minimize Light Pollution	Not Applicable	1	12	-	-	-	-	-	-
		QL1.6 Minimize Construction Impacts	Assessed	1	8	-	-	-	-	-	-
	Mobility	QL2.1 Improve Community Mobility Access	Not Applicable	1	14	-	-	-	-	-	-
		QL2.2 Encourage Sustainable Transportation	Not Applicable	5	16	c	-	-	-	-	-
		QL2.3 Improve Access & Wayfinding	Not Applicable	1	14	-	-	-	-	-	-
	Community	QL3.1 Advance Equity & Social Justice	Not Applicable	3	18	-	-	-	-	-	-
		QL3.2 Preserve Historic & Cultural Resources	Not Applicable	2	18	-	-	-	-	-	-
		QL3.3 Enhance Views & Local Character	Not Applicable	1	14	-	-	-	-	-	-
		QL3.4 Enhance Public Space & Amenities	Not Applicable	1	14	-	-	-	-	-	-

Fig. 5-1, Selected indicators for Quality of Life [elaboration from Institute for Sustainable Infrastructure, 2018].

The 13 credits for quality of life, have, following the ICMQ approach, few connections with the EU sustainability objectives. It is more about the OBJ 5 around pollution prevention. Driving down the credits to ground improvement context we considered applicable also those credits where the construction methods could impact on the quality of life of the stakeholders, particularly the credits from QL1.3 to QL1.5. All the others could be better taken into account when assessing a more general project that a specific geotechnical one. These are the credits applicable in the framework for ground improvement techniques:

- ***QL1.2 Enhance Public Health & Safety, related to DNSH OBJ5 subpoints b, c, d.***
  - Any Envision project must meet all safety and health regulations as required by law. This credit recognizes the opportunities many projects have to exceed minimum regulatory requirements, or to improve health and/or safety within a project or community in other ways. The credit assesses the degree to which infrastructure projects contribute to increased safety and health benefits on the project site, surrounding sites, and the broader community. Envision does not in any way replace, supersede, or create exceptions for existing local, state/provincial, or national health and safety regulations.
  - Project teams and owners should consider how improving the safety and health benefits of the project, its surroundings, and the broader community, and communicating these benefits to stakeholders, can help combat negative perceptions that lead to conflicts and project delays (e.g.,"NIMBY"). Enhancing and emphasizing positive health and safety benefits can help change public perception about the value of infrastructure.
- ***QL1.3 Improve Construction Safety, related to DNSH OBJ5, subpoints c, d.***
  - This credit addresses the critical goal of improving health and safety practices during construction. Having and promoting a common focus on health and safety throughout the construction industry has benefits that extend beyond the individual project.
  - Improved construction safety can also have benefits beyond the protection of health and human life. Companies that have a record in job site safety attract better employees, have higher retention rates, and are more competitive in the marketplace. The rigor of applying, training, and adhering to health and safety procedures can also increase productivity by standardizing job site activities.
  - Enhanced health and safety practices are encouraged beyond industry norms. However, a novel approach may introduce risks that were not present prior to instituting the new program or technology. Project teams should conduct hazard analyses and develop construction safety plans to address risks associated with using new materials, technologies, and/or methodologies.
  - Days Away, Restrictions, or Transfers (DART) rates are a mathematical calculation of the number of recordable incidents per 100 full-time employees that resulted in lost or restricted days or job transfer due to work-related injuries or illnesses. From this data, many leading construction companies find that the return on investment for implementing better health and safety standards is higher than the cost and lost time associated with job site incidents.
- ***QL1.4 Minimize Noise & Vibration.***
  - This credit addresses noise and vibrations during project operations. Credit QL1.6 Minimize Construction Impacts addresses construction-related noise and vibrations. "Noise" is defined as an unwanted or disturbing sound. It becomes unwanted when it interferes with normal activities or diminishes quality of life.
  - Noise is a common complaint against a wide variety of infrastructure projects. Noise can have significant negative health effects, including hearing impairment, hypertension, and sleep disturbance. It can also reduce performance in cognitive tasks. Residential property values may be improved as a result of reduced ambient noise levels. Noise pollution can also interfere with animal communication, predator-prey relations, and mating habits, particularly among birds.
  - Addressing operational noise is an important step for incorporating infrastructure into communities and the environment. This is particularly true during stakeholder engagement to

demonstrate that community concerns are being heard. Setting noise reduction targets can often provide an impetus to consider creative and innovative alternative solutions.

- ***QL1.5 Minimize Light Pollution.***
    - This credit follows the guidelines of the Model Lighting Ordinance issued by the International Dark-Sky Association and the Illuminating Engineering Society (IES) of North America. The Model Lighting Ordinance outdoor lighting template utilizes the IES TM-15-11 "BUG" (Backlight, Uplight, and Glare) classification of outdoor lighting fixtures and is designed to help municipalities develop outdoor lighting standards that reduce glare, light trespass, and skyglow.
    - High levels of ambient light are undesirable for humans from both an aesthetic and health perspective. Light pollution has the potential to disrupt circadian rhythms and human sleep patterns, which may have numerous health implications. Light spillage also disturbs nocturnal animals and interferes with sensitive environments, including open space, wilderness parks and preserves, areas near astronomical observatories, and other light-sensitive habitats. Finally, the cumulative exterior light directed upward into the sky because of inappropriate lighting represents a massive waste of energy.
    - Well-designed lighting can maintain adequate light levels on the ground while reducing light pollution by using lighting more efficiently. Many cities and communities may be using more light than is necessary and could benefit from a lighting-needs audit and assessment. By directing light only to where it is needed, project lighting can be more efficient and save costs.
- ***QL1.6 Minimize Construction Impacts.***
    - Infrastructure projects are long-term projects that may take years to complete construction. During this time, it is important for the project to have minimal negative impacts on the surrounding community. While completed infrastructure projects may go unseen by the public, the construction phase is often a time when a new project is most visible. Project teams can harness this as an opportunity to exemplify best practices. In doing so, they instill trust in the community, and can make further strides toward project acceptance.
    - There are a range of ways a project team can consider a community's needs during the construction phase. Similar to the operational impacts on a community, project teams consider the same impacts during construction because they may be elevated in this phase. Noise, vibrations, and light pollution should be minimized during construction so as to reduce disturbances to surrounding communities. Further, projects in construction should never impede on a community's safety or mobility.

			Credit Assessmen Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular econom transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Leadership	Collaboration	LD1.1 Provide Effective Leadership & Commitment	Not Applicable	2	18	-	-	-	-	-	-
		LD1.2 Foster Collaboration & Teamwork	Not Applicable	2	18	-	-	-	-	-	-
		LD1.3 Provide for Stakeholder Involvement	Not Applicable	3	18	-	-	-	-	-	-
		LD1.4 Pursue Byproduct Synergies	Assessed	3	18	-	-	-	a, c, e, f, g, h, j, k	-	-
	Planning	LD2.1 Establish a Sustainability Management Plan	Not Applicable	4	18	-	-	-	-	-	-
		LD2.2 Plan for Sustainable Communities	Not Applicable	4	16	-	-	-	-	-	-
		LD2.3 Plan for Long-Term Monitoring & Maintenance	Not Applicable	2	12	-	-	-	b, e	-	-
		LD2.4 Plan for End-of-Life	Not Applicable	2	14	-	-	-	b, e	-	-
	Economy	LD3.1 Stimulate Economic Prosperity & Development	Not Applicable	3	20	-	-	-	-	-	-
		LD3.2 Develop Local Skills & Capabilities	Not Applicable	2	16	-	-	-	-	-	-
		LD3.3 Conduct a Life-Cycle Economic Evaluation	Assessed	5	14	-	-	-	-	-	-

Fig. 5-2, Selected indicators for Leadership [elaboration from Institute for Sustainable Infrastructure, 2018].

When it comes to the 11 credits of the category of Leadership, the connection between EU and Envision is focused on the synergies for reuse of by-products, both to match the objectives of circular economy and of pollution prevention. We decided to significantly reduce the credits applicable to the ground improvement cases mainly because of their more 'general' applicability and we kept those related to life cycle and sustainability management because they are an important part of the case studies that we will analyse. These are the credits considered applicable to our case:

- ***LD1.4 Pursue Byproduct Synergies, related to DNSH OBJ4, subpoints a, c, e, f, g, h, j, k.***
    - Though byproducts are most commonly thought of as solid waste, they may include a wide variety of excess resources. True byproduct synergy, or reuse, involves identification and cost-effective use of unwanted waste or excess resources (e.g., materials, energy/heat, gas emissions, effluent, water, services, capacity). Byproduct synergies can be accomplished in two ways: finding opportunities for a project's excess resources to be beneficially reused off site, or incorporating off-site excess resources into the project.
    - The term "byproduct synergy" may also be known as "industrial ecology," through its expression in "eco-industrial parks," or by the broader concepts of "circular economy." Whatever the preferred terminology, the classification of excess resources or services as "waste" is inherently inefficient. Everything has value. In a circular economy, all excess resources or services are directed to local beneficial use. These interconnected systems are more resilient by eliminating waste and reducing dependence on external sources. True circular economies are rare, but every project can contribute toward growing circular economies by investigating opportunities for beneficial reuse.
- ***LD2.1 Establish a Sustainability Management Plan, related to DNSH OBJ4, subpoints b, e.***
    - This credit addresses the importance of supporting the achievement of sustainability goals through the structure of plans and policies. Given the long timelines, complex interorganizational cooperation, and varied consultants and contractors, it is critical to have a sustainability management plan to establish expectations and ensure that sustainability goals and objectives are communicated and carried through project delivery. When time and budgets are limited, sustainability criteria must have this level of institutional support in order to be successful. By clearly establishing roles, responsibilities, and expectations, project owners and project teams realize efficiencies in avoided conflicts, duplications, or miscommunication. Having a clear prioritization of goals helps consultants and contractors correctly devote their time and resources in order to deliver the best possible project for their client.
    - A sustainability management plan enables an organization to set goals, objectives, and policies; instigate plans and programs; review performance against a plan; and take corrective actions across the full dimensions of sustainability. The International Organization for Standardization (ISO) 14004 standard for social and environmental management plans provides guidance on developing a sustainability management plan.
- ***LD3.3 Conduct a Life-Cycle Economic Evaluation, related to DNSH OBJ4, subpoints b, e.***
    - This credit provides incentives for, and recognition of, the use of sound, industry-accepted economic analysis to provide a better measurement of the value of a project and ultimately encourage greater levels of sustainability. Taking a life-cycle economic approach to project evaluation can enhance decision making by encouraging the effective management of resources and assets that ultimately lead to more sustainable projects. Life-cycle economic evaluations allow for a comprehensive assessment to better understand the trade-offs of upfront capital costs and the longer-term anticipated operational savings that may accrue from sustainable design. An intended outcome of infrastructure is often to generate benefits and/or reduce negative impacts to the community, the environment, and broader society. Economic analysis can be used to measure and value these benefits, which are typically assessed only qualitatively.
    - Using rigorous economic analysis to more fully assess investments can help organizations best use its funds among competing capital projects. By using a life-cycle approach, design alternatives can be compared on a present value basis, which may ultimately prove the business case for more sustainable projects.

- Life-cycle cost analysis (LCCA) is one of several evaluation techniques commonly used to compare and evaluate the financial feasibility of various design alternatives over an assumed service life cycle. LCCA provides a more informed perspective of the total financial costs of the project and allows a more direct comparison of competing projects. At a minimum it is necessary to make sure the project is assessing capital, operations and management, replacement cost, and any residual value over a consistent time period for all alternatives, while incorporating discounting techniques to factor in the time-value-of-money to compare multiple different projects on a common basis.
- While life-cycle cost analysis provides greater rigor and insight in the planning process, it does not assess the social and environment benefits generated by the project. A comprehensive sustainability cost benefit analysis measures the broader financial, social, and environmental benefits of the project. This extended analysis further quantifies those impacts and then monetizes them. A sustainability cost benefit analysis adds the monetary values of social and environmental impacts to the life-cycle financial results (LCCA) to comprehensively measure the sustainability impacts. It allows a direct assessment of the trade-offs for varying levels of financial costs, environmental quality, social impacts, and resiliency, and allows decision makers to identify those projects that are the most-beneficial and cost-effective.
- Often, upfront capital costs are the key driver in planning decisions; however this omits the life-cycle costs of the project, risks and uncertainty, or the broader outcomes that impact the environment and society. As a result, owners may overlook sustainability-related investments with higher upfront capital costs, but which ultimately produce cost savings over the life-cycle of the project from lower utility costs, operations and maintenance costs, or less replacement costs.
- There is significant guidance that can be found regarding the specific steps to follow in conducting a life-cycle economic evaluation. There is no one prescribed approach that is recommended for this credit; however, a general approach is as follows:
    - Define the base case.
    - List feasible alternatives including no-build—these can be design elements or entire projects.
    - Specify categories of costs and benefits.
    - Quantify costs and benefits as incremental to the base case.
    - Monetize costs and benefits.
    - Identify and incorporate risks into the analysis.
    - Discount future cash flows to calculate net present value.

We decided to keep also the LD2.1 and LD3.3 credits because of their relevance with respect to life cycle assessment, that will become instrumental in the next phases of our research.

			Credit Assessment Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular econom transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Resource Allocation	Materials	RA1.1 Support Sustainable Procurement Practices	Assessed	3	12	-	-	-	d	d	d
		RA1.2 Use Recycled Materials	Assessed	4	16	d	-	-	c, e, g	-	-
		RA1.3 Reduce Operational Waste	Not Applicable	3	14	c	-	-	f, g, h, j, k	-	-
		RA1.4 Reduce Construction Waste	Assessed	4	16	c	-	-	f, g, h, j, k	-	-
		RA1.5 Balance Earthwork On Site	Not Applicable	2	8	c	-	-	f	a	b, d
	Energy	RA2.1 Reduce Operational Energy Consumption	Not Applicable	6	26	a	-	-	-	-	-
		RA2.2 Reduce Construction Energy Consumption	Assessed	1	12	c	-	-	-	-	-
		RA2.3 Use Renewable Energy	Assessed	5	24	a	-	-	-	-	-
		RA2.4 Commission & Monitor Energy Systems	Not Applicable	3	14	b	-	-	-	-	-
	Water	RA3.1 Preserve Water Resources	Not Applicable	3	12	-	-	a, c	-	-	-
		RA3.2 Reduce Operational Water Consumption	Not Applicable	4	22	-	-	b, c	-	-	-
		RA3.3 Reduce Construction Water Consumption	Assessed	1	8	-	-	b, c	-	-	-
		RA3.4 Monitor Water Systems	Not Applicable	1	12	-	-	-	-	-	-

Fig. 5-3, Selected indicators for Resource Allocation [elaboration from Institute for Sustainable Infrastructure, 2018].

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

- ***RA1.1 Support Sustainable Procurement Practices, related to DNSH OBJ4, OBJ5, OBJ6, subpoint d for all.***
    - This credit encourages choosing suppliers that incorporate sustainability into their policies and daily practices and operations. Project teams should give preference to suppliers that have taken into account the environmental, economic, and social impacts of their products and have active programs in place for performance improvement.
    - Infrastructure projects are major consumers of materials, and owners should consider their ability to influence higher sustainability performance upstream in the material manufacturing chain. As owners and project teams request and require sustainability disclosures, this information will become increasingly available and easier to obtain. Such changes have already occurred in the material supply chains for buildings. While this credit is linked to CR1.1 Reduce Net Embodied Carbon, it expands beyond the impacts of per unit material production to include the environmental impacts of the entire manufacturing process.
    - Supplier integrity and ethical behavior are important considerations. Establishing policies for the procurement of sustainably manufactured products and materials helps safeguard the reputation and achievements of the project, and all organizations involved, from the possibility of future disclosures that project materials were produced in unsafe or environmentally damaging conditions.
- ***RA1.2 Use Recycled Materials, related to DNSH OBJ4, subpoints c, e, j and OBJ1, subpoint d.***
    - The purpose of this credit is to reduce the use of virgin natural resources and avoid sending useful materials to landfills. Using recycled, reused, and renewable materials and products, including existing structures and materials on site, reduces demand for virgin materials and the embodied carbon emissions and environmental degradation attributed to their extraction and processing. Using these materials also reduces waste and supports the market for recycled and reused materials. Project teams should consider how salvaging or repurposing existing materials or structures can significantly reduce demand for new construction materials as well as project costs. The reuse of existing materials or elements may also have a significant cultural or aesthetic value, such as street lamps, sidewalk pavers, bridges, and more.
- ***RA1.4 Reduce Construction Waste, related to DNSH OBJ1, subpoint c and OBJ4 subpoints f, g, h, j, k.***
    - The goal of this credit is to reduce construction waste and divert waste streams from disposal to recycling and reuse. Project teams can improve performance by considering the ability of waste generated during construction to be recycled or beneficially reused, implementing waste management plans to capture waste, and identifying possible recycling centers with appropriate capabilities.
    - When considering the extra time or effort involved in collecting and diverting construction waste, consideration should be given to cost savings in dumping fees. Additionally, some recycled materials such as scrap metal have a positive value. Achieving high rates of construction waste diversion is often about the institutional training and operating procedures of the organizations and companies involved. Infrastructure owners should consider these capabilities when choosing project teams.
- ***RA2.2 Reduce Construction Energy Consumption, related to DNSH OBJ1, subpoint c.***

  - This credit addresses the important need to reduce construction energy consumption. As construction energy use is closely linked to emissions, many actions in this credit address energy efficiency, energy reduction, renewable energy use, and reduced emissions. Therefore, in addition to other Resource Allocation credits, RA2.2 Reduce Construction Energy
  - Consumption is also connected to CR1.1 Reduce Net Embodied Carbon, and CR1.2 Reduce Greenhouse Gas Emissions.
  - Significant cost savings can be achieved by reducing fuel consumption during construction. Project teams should consider the secondary and tertiary benefits of reduced truck trips, improved air quality, and support for renewable energy systems. While single actions like replacing fluorescent lights with light emitting diodes (LEDs) is a positive first step, large energy savings can be achieved when considering broader construction logistics and coordination.
- ***RA2.3 Use Renewable Energy, related to DNSH OBJ1, subpoint c.***
  - While reducing energy use is the primary goal, a net-zero energy society will require significant investment in renewable energy sources. When appropriate, renewable energy can be generated on site to help reduce the need for fossil fuel sources. However, it is important to note that large-scale off-site renewable energy sources, such as wind farms, large hydroelectric facilities, or solar arrays, are often more efficient. It can be challenging to demonstrate a direct connection to these sources and ensure that their energy generation is not double-counted by other projects. Project teams should evaluate the feasibility of renewable energy, including nontraditional energy sources, to effectively increase the portion of operational energy that comes from renewable sources.
- ***RA3.3 Reduce Construction Water Consumption, related to DNSH OBJ3, subpoints b. c.***
  - This credit addresses the potential to reduce water consumption during construction. Overuse of water not only depletes waterbodies and lowers groundwater levels, but the treatment of water consumes large amounts of energy. In many cases, it is not necessary to use potable (i.e., drinkable) water for the intended task. Greywater (e.g., water that has been used for cleaning or other purposes and has not come into contact with feces), recycled water, and stormwater are alternatives to potable water use, especially in construction. Reducing water consumption during construction can reduce the environmental impact of the project.

			Credit Assessment Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular econom transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Natural World	Siting	NW1.1 Preserve Sites of High Ecological Value	Not Applicable	2	22	f	-	-	-	-	a, d
		NW1.2 Provide Wetland & Surface Water Buffers	Not Applicable	2	20	-	-	c	-	-	a
		NW1.3 Preserve Prime Farmland	Not Applicable	2	16	f	-	-	-	-	c
		NW1.4 Preserve Undeveloped Land	Not Applicable	3	24	f	-	-	-	-	b, d
	Conservation	NW2.1 Reclaim Brownfields	Not Applicable	11	22	-	-	-	-	a, c, d	b
		NW2.2 Manage Stormwater	Not Applicable	2	24	-	a, b	a	-	a	-
		NW2.3 Reduce Pesticide & Fertilizer Impacts	Not Applicable	1	12	f	-	a, c	-	a	b, d
		NW2.4 Protect Surface & Groundwater Quality	Assessed	2	20	-	-	d	-	a	a
	Ecology	NW3.1 Enhance Functional Habitats	Not Applicable	2	18	-	-	-	-	-	a, d
		NW3.2 Enhance Wetland & Surface Water Functions	Not Applicable	3	20	-	-	c, d	-	-	a
		NW3.3 Maintain Floodplain Functions	Not Applicable	1	14	f	a, b	c	-	-	a
		NW3.4 Control Invasive Species	Not Applicable	1	12	-	-	-	-	-	b, d
		NW3.5 Protect Soil Health	Assessed	3	8	f	-	-	-	a	b, d

Fig. 5-4, Selected indicators for Natural World [elaboration from Institute for Sustainable Infrastructure, 2018].

The category of Natural World, with its 13 credits, is very much related with the final scope of the project that the ground treatment is a ‘special’ part of. Therefore, many credits have been considered non applicable: we decided to keep those related with stormwater and to the protection of soil health because they are very relevant to geotechnics. These are the credits:

- ***NW2.2 Manage Stormwater, related to DNSH OBJ2, subpoints a,b and OBJ3, subpoint a and OBJ5, subpoint a.***

    - Stormwater is an increasing concern and source of risk for communities. Climate change is making precipitation rates increasingly unpredictable, with more intense storms becoming common. Historic design standards and regulations may not be sufficient to prepare communities for the future. Infrastructure owners should consider how taking opportunities to improve stormwater management systems reduces their risk exposure. There are significant cost savings in addressing stormwater outside wastewater treatment facilities. Reducing the demand on wastewater treatment prolongs the ability of existing facilities to provide sufficient capacity without need for expansion.
    - Improperly managed stormwater can have serious environmental impacts. Increased surface runoff typically leads to increased stream and channel erosion, downstream flooding, water temperatures (and thereby lowered dissolved oxygen in receiving waters), and concentration of pollutants reaching surface waters. It can deposit sediment and pollutants into waterways and warm historically cold-water streams. This can negatively impact aquatic life as native species are replaced with more pollutant-tolerant warm-water species.
    - Natural systems for stormwater management, often referred to as "green infrastructure," provide multiple benefits. Bioswales and rain gardens can provide community beautification, reduce heat islands, and present an opportunity to educate the public on the importance of stormwater management. Project teams should consider how incorporating low-impact development measures can reduce and mitigate potential negative impacts associated with increased runoff.
- ***NW2.4 Protect Surface & Groundwater Quality, related to DNSH OBJ3, subpoint d and OBJ5, subpoint a and OBJ6, subpoint a.***
    - The goal of this credit is to preserve water resources by incorporating measures to prevent pollutants from contaminating surface water and groundwater and monitor impacts during construction and operations. Groundwater is a widely used source of drinking water. Protecting wellheads and groundwater recharge areas reduces the chances of groundwater contamination and protects natural water purification processes. In addition, aquatic ecosystems depend on a particular set of water conditions. Changes to any of these factors can adversely affect aquatic life and groundwater quality. Aquatic ecosystems are threatened by changes in pH, decreases in water clarity, and increases in temperature, dissolved solids, coliform bacteria, toxic substances, and nutrients (especially phosphorus and nitrogen).
    - Leaks, spills, and other sources of contamination have serious environmental, social, and economic costs with prevention almost always being more economical than cleanup. Contamination takes many forms but can kill flora and fauna, destroy habitats, and cause illness or premature death in humans.
    - Concerns regarding equipment and facilities containing potentially polluting substances include fuel and chemical storage, pipelines, piles of raw materials, and process areas. At the construction stage, potential sources of groundwater and surface water contamination include spills and leaks from tanks, pipes, and construction vehicles; leaching of pollutants from raw or waste materials; and releases of pollutants from the demolition of previously completed projects.
- ***NW3.5 Protect Soil Health related to DNSH OBJ1, subpoint f and OBJ5, subpoint a and OBJ6, subpoint b,d.***
    - Climate, organisms, relief, parent material, and time (CORPT) are the factors of soil formation. Given enough time, if all other factors are held constant, soils that have been mechanically disturbed can naturally restore themselves. However, because soil formation is slow, the natural process of soil recovery can take millennia. Various human activities can be used to enhance the ability of mechanically disturbed soils to function as they did before being disturbed. This process is referred to as "soil restoration." The details of which activities

should be used are highly dependent on the original soil type, the factors that formed it, and the functions that land managers wish to recover. In the context of this credit, soil restoration refers to the quality and condition of the soil and does not refer to keeping soil on site (this is addressed in RA1.5 Balance Earthwork on Site).

- o Construction activities can disturb soil health in many ways, the most common being compaction. Disturbed soils cannot hold water, nutrients, or carbon as well as natural, undisturbed soils. Disturbed soil is less capable of absorbing floodwaters or sustaining vegetation. Compaction caused by construction equipment can kill surrounding plants and trees, and prevent future plant growth.

			Credit Assessment Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular econom transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Climate and Resilience	Emissions	CR1.1 Reduce Net Embodied Carbon	Assessed	5	20	d	-	-	c, d	-	-
		CR1.2 Reduce Greenhouse Gas Emissions	Assessed	3	26	e, f	-	-	-	-	-
		CR1.3 Reduce Air Pollutant Emissions	Assessed	2	18	-	-	-	-	a, b	-
	Resilience	CR2.1 Avoid Unsuitable Development	Not Applicable	3	16	-	a, b	c	-	-	-
		CR2.2 Assess Climate Change Vulnerability	Not Applicable	8	20	-	a, b	-	-	-	-
		CR2.3 Evaluate Risk and Resilience	Not Applicable	11	26	-	a, b	c	-	b	-
		CR2.4 Establish Resilience Goals and Strategies	Not Applicable	8	20	-	-	-	-	-	-
		CR2.5 Maximize Resilience	Not Applicable	11	26	-	-	-	-	-	-
		CR2.6 Improve Infrastructure Integration	Not Applicable	2	18	-	-	-	-	-	-

Fig. 5-5, Selected indicators for Climate and Resilience [elaboration from Institute for Sustainable Infrastructure, 2018].

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

- ***CR1.1 Reduce Net Embodied Carbon related to DNSH OBJ1, subpoint b and OBJ4, subpoints c and d.***
  - o This credit addresses the embodied carbon of materials used over the life of the project. This combines concepts of sourcing local materials, using materials more efficiently, and using lower-impact materials in order to reduce the combined environmental impacts of material use. In the calculations, carbon is used as a proxy unit of measure to compare various impacts across the entire supply chain of material consumption. One stage of this supply chain involves raw material extraction/harvesting, refinement, and manufacturing into products. The second involves transportation of the materials from the manufacturer to their final destination on site. By designing projects to use less material, use material efficiently, or specifying materials with lower embodied carbon, as well as reducing transportation distances, project teams can reduce the overall impact of the project.
  - o Material use is specifically addressed over the life of the project, including the necessary replacement or renewal of materials. Often, materials with slightly higher initial embodied carbon will have a lower net embodied carbon over the life of the project if they are more durable and less likely to require repair or replacement.
- ***CR1.2 Reduce Greenhouse Gas Emissions, related to DNSH OBJ1, subpoints e, f.***
  - o This credit addresses greenhouse gas emissions during operations and the project's contribution in reducing the impacts of climate change. The embodied carbon of materials is specifically addressed in CR1.1 Reduce Net Embodied Carbon. Emission of greenhouse gases during construction is addressed in RA2.2 Reduce Construction Energy Consumption.
  - o The increased release of carbon dioxide (CO2) and other greenhouse gases (GHGs) has caused a significant increase in the concentration of CO2 in the atmosphere, enhancing the greenhouse effect. The subsequent increase in the average temperature of the earth's surface causes various cascading effects, including melting glaciers, arctic sea ice loss, sea level rise, increased ocean temperatures, increased ocean acidity, changing vegetation patterns, increased range of disease vectors, decreased snowmelt, changing precipitation patterns, increased

flooding, increased storm intensity, and increased storm frequency, to name a few. This can have many unintended consequences such as flooding when historic periods of snowfall change to rain, drought from increased evaporation and lack of snowmelt, loss of coral reefs and aquatic biodiversity from ocean acidification, and food scarcity as increased temperatures reduce crop production. Reducing the emission of GHGs now will help mitigate the effects of climate change in the future.

- ***CR1.3 Reduce Air Pollutant Emissions, related to DNSH OBJ5, subpoints a, b.***
    - The criteria pollutants include carbon singlexide, nitrogen oxides, sulfur dioxide, suspended particulate matter smaller than PM-10, ozone, lead, and volatile organic compounds. These pollutants damage human health, property, and the environment. Those most at risk are children, the elderly, and people with lung diseases such as asthma, chronic bronchitis, and emphysema. Dust and odors also can cause a nuisance for nearby residents, reduce property values, and aggravate the aforementioned lung conditions.
- ***CR2.5 Maximize Resilience.***
    - This credit addresses the implementation of strategies and systems to increase the resilience of the project. While it can be assessed independently, it should be considered as a continuation of the previous resilience credits. After identifying vulnerabilities and, it is time to implement the strategies on the project. This credit is independent because successful and effective implementation requires a range of actions beyond the resilience strategies themselves.

We decided to include CR2.5 as a general mention to the need for resilience also at the level of ground improvement.

As a synthesis of this process the structure of the sustainability assessment that we will be using for analyzing our ground treatment cases is the following one.

			Credit Assessmen Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular econom transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Quality of Life	Wellbeing	QL1.1 Improve Community Quality of Life	Not Applicable	2	26	-	-	-	-	-	-
		QL1.2 Enhance Public Health & Safety	Not Applicable	2	20	-	-	-	-	b, c, d	-
		QL1.3 Improve Construction Safety	Not Applicable	2	14	-	-	-	-	c, d	-
		QL1.4 Minimize Noise & Vibration	Assessed	1	12	-	-	-	-	-	-
		QL1.5 Minimize Light Pollution	Not Applicable	1	12	-	-	-	-	-	-
		QL1.6 Minimize Construction Impacts	Assessed	1	8	-	-	-	-	-	-
	Mobility	QL2.1 Improve Community Mobility Access	Not Applicable	1	14	-	-	-	-	-	-
		QL2.2 Encourage Sustainable Transportation	Not Applicable	5	16	c	-	-	-	-	-
		QL2.3 Improve Access & Wayfinding	Not Applicable	1	14	-	-	-	-	-	-
	Community	QL3.1 Advance Equity & Social Justice	Not Applicable	3	18	-	-	-	-	-	-
		QL3.2 Preserve Historic & Cultural Resources	Not Applicable	2	18	-	-	-	-	-	-
		QL3.3 Enhance Views & Local Character	Not Applicable	1	14	-	-	-	-	-	-
		QL3.4 Enhance Public Space & Amenities	Not Applicable	1	14	-	-	-	-	-	-

			Credit Assessmen Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular econom transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Leadership	Collaboration	LD1.1 Provide Effective Leadership & Commitment	Not Applicable	2	18	-	-	-	-	-	-
		LD1.2 Foster Collaboration & Teamwork	Not Applicable	2	18	-	-	-	-	-	-
		LD1.3 Provide for Stakeholder Involvement	Not Applicable	3	18	-	-	-	-	-	-
		LD1.4 Pursue Byproduct Synergies	Assessed	3	18	-	-	-	a, c, e, f, g, h, j, k	-	-
	Planning	LD2.1 Establish a Sustainability Management Plan	Not Applicable	4	18	-	-	-	-	-	-
		LD2.2 Plan for Sustainable Communities	Not Applicable	4	16	-	-	-	-	-	-
		LD2.3 Plan for Long-Term Monitoring & Maintenance	Not Applicable	2	12	-	-	-	b, e	-	-
		LD2.4 Plan for End-of-Life	Not Applicable	2	14	-	-	-	b, e	-	-
	Economy	LD3.1 Stimulate Economic Prosperity & Development	Not Applicable	3	20	-	-	-	-	-	-
		LD3.2 Develop Local Skills & Capabilities	Not Applicable	2	16	-	-	-	-	-	-
		LD3.3 Conduct a Life-Cycle Economic Evaluation	Assessed	5	14	-	-	-	-	-	-

			Credit Assessmen Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular econom transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Resource Allocation	Materials	RA1.1 Support Sustainable Procurement Practices	Assessed	3	12	-	-	-	d	d	d
		RA1.2 Use Recycled Materials	Assessed	4	16	d	-	-	c, e, g	-	-
		RA1.3 Reduce Operational Waste	Not Applicable	3	14	c	-	-	f, g, h, j, k	-	-
		RA1.4 Reduce Construction Waste	Assessed	4	16	c	-	-	f, g, h, j, k	-	-
		RA1.5 Balance Earthwork On Site	Not Applicable	2	8	c	-	-	f	a	b, d
	Energy	RA2.1 Reduce Operational Energy Consumption	Not Applicable	6	26	a	-	-	-	-	-
		RA2.2 Reduce Construction Energy Consumption	Assessed	1	12	c	-	-	-	-	-
		RA2.3 Use Renewable Energy	Assessed	5	24	a	-	-	-	-	-
		RA2.4 Commission & Monitor Energy Systems	Not Applicable	3	14	b	-	-	-	-	-
	Water	RA3.1 Preserve Water Resources	Not Applicable	3	12	-	-	a, c	-	-	-
		RA3.2 Reduce Operational Water Consumption	Not Applicable	4	22	-	-	b, c	-	-	-
		RA3.3 Reduce Construction Water Consumption	Assessed	1	8	-	-	b, c	-	-	-
		RA3.4 Monitor Water Systems	Not Applicable	1	12	-	-	-	-	-	-

			Credit Assessmen Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular econom transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Natural World	Siting	NW1.1 Preserve Sites of High Ecological Value	Not Applicable	2	22	f	-	-	-	-	a, d
		NW1.2 Provide Wetland & Surface Water Buffers	Not Applicable	2	20	-	-	c	-	-	a
		NW1.3 Preserve Prime Farmland	Not Applicable	2	16	f	-	-	-	-	c
		NW1.4 Preserve Undeveloped Land	Not Applicable	3	24	f	-	-	-	-	b, d
	Conservation	NW2.1 Reclaim Brownfields	Not Applicable	11	22	-	-	-	-	a, c, d	b
		NW2.2 Manage Stormwater	Not Applicable	2	24	-	a, b	a	-	a	-
		NW2.3 Reduce Pesticide & Fertilizer Impacts	Not Applicable	1	12	f	-	a, c	-	a	b, d
		NW2.4 Protect Surface & Groundwater Quality	Assessed	2	20	-	-	d	-	a	a
	Ecology	NW3.1 Enhance Functional Habitats	Not Applicable	2	18	-	-	-	-	-	a, d
		NW3.2 Enhance Wetland & Surface Water Functions	Not Applicable	3	20	-	-	c, d	-	-	a
		NW3.3 Maintain Floodplain Functions	Not Applicable	1	14	f	a, b	c	-	-	a
		NW3.4 Control Invasive Species	Not Applicable	1	12	-	-	-	-	-	b, d
		NW3.5 Protect Soil Health	Assessed	3	8	f	-	-	-	a	b, d

			Credit Assessmen Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular econom transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Climate and Resilience	Emissions	CR1.1 Reduce Net Embodied Carbon	Assessed	5	20	d	-	-	c, d	-	-
		CR1.2 Reduce Greenhouse Gas Emissions	Assessed	3	26	e, f	-	-	-	-	-
		CR1.3 Reduce Air Pollutant Emissions	Assessed	2	18	-	-	-	-	a, b	-
	Resilience	CR2.1 Avoid Unsuitable Development	Not Applicable	3	16	-	a, b	c	-	-	-
		CR2.2 Assess Climate Change Vulnerability	Not Applicable	8	20	-	a, b	-	-	-	-
		CR2.3 Evaluate Risk and Resilience	Not Applicable	11	26	-	a, b	c	-	b	-
		CR2.4 Establish Resilience Goals and Strategies	Not Applicable	8	20	-	-	-	-	-	-
		CR2.5 Maximize Resilience	Not Applicable	11	26	-	-	-	-	-	-
		CR2.6 Improve Infrastructure Integration	Not Applicable	2	18	-	-	-	-	-	-

	Credit Assessmen Status	Total Minimum Points	Total Maximum Points	Climate Change mitigation OBJ1	Climate Change adaptation OBJ2	Sustainable use of water and marine resource OBJ3	Circular econom transition OBJ4	Pollution prevention OBJ5	Biodoversity and ecosystem protection OBJ6
Total Points	**All Credits Assessed**	**232**	**1000**						
Possible Award Level:	**59 Not Assessed**								

Fig. 5-6, The framework for Ground Improvement Techniques as a construction process [elaboration from Institute for Sustainable Infrastructure, 2018].

At a glance, it can be noted that all the DNSH objectives are touched through this dedicated assessment and that, despite the very specific technology that we are considering, this tool can keep the focus of designers and constructors on the more general goal of systemic sustainability. At the same time, the sustainability analysis conducted with this tool, can be easily integrated in wider analyses (i.e. at the whole project scope level) both with Envision and DNSH criteria.

A potential tool for qualitatively guiding the analysis of a construction process and frame sustainable strategic choices. Just having an overview of the indicators tells a lot: they span from the working site (noise, construction impacts on communities), to decision making tools (byproduct synergies, LCA, LCCA), to resources exploitation (sustainable procurement, recycle, reuse, waste, energy kind and consumption, water consumption), to the surrounding ecosystem (groundwater quality, soil health) to climate change (embodied carbon, GHG emissions, air quality). Comparing this framing with a pure impact analysis, the difference lies in the fact that the focus is put firstly on strategic choices and then on consequences. Moreover, the combination of the Envision protocol and the EU taxonomy creates consistency in the approach: different stakeholders find their point of view clarified and different designers or constructors, no matter where in EU can approach sustainability in a very consistent way.

6 A methodological approach to assess sustainability in geotechnical construction techniques

6.1 General view of the methodology

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

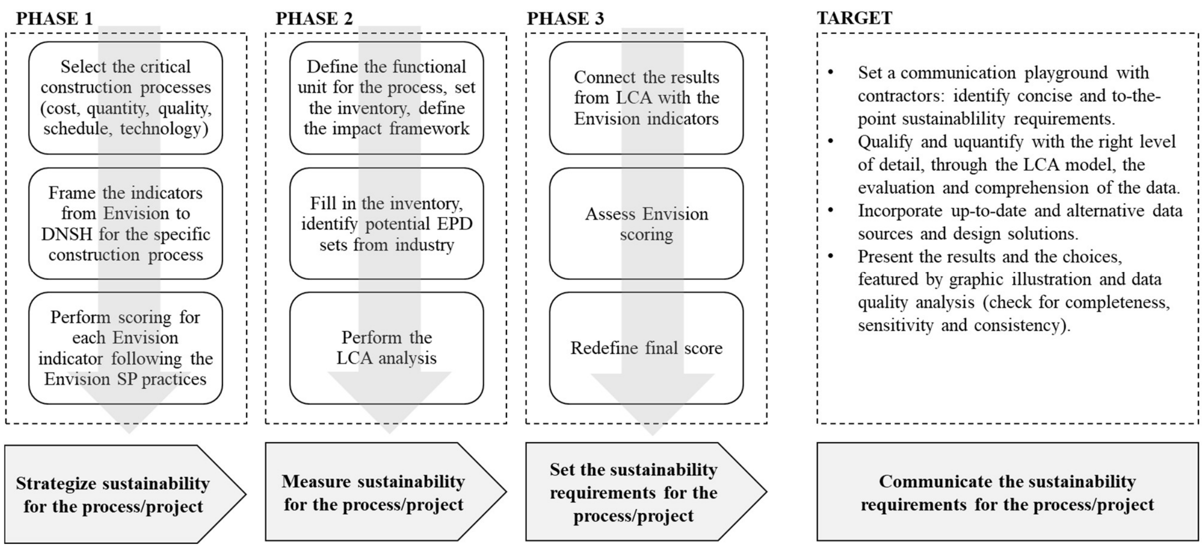


Fig. 6-1, The Three Phased Method.

The first phase of the method: a tool for qualitatively guiding the analysis of a construction process and frame its sustainable strategic choices. Just having an overview of the indicators of the Envision/DNSH framework presented in the previous chapter tells a lot: they span from improving the working site (noise, construction impacts on communities) to decision-making tools (byproduct synergies, LCA, LCCA), to resource exploitation (sustainable procurement, recycle, reuse, waste, energy kind and consumption, water consumption), to the surrounding ecosystem (groundwater quality, soil health), to climate change (embodied carbon, GHG emissions, air quality). When this this framing is compared with a pure impact analysis, the difference lies in the focus being put first on strategic choices and then on consequences. Moreover, combining the Envision protocol and the EU taxonomy creates consistency in the approach: different stakeholders find their point of view clarified, and different designers or constructors, no matter where in the EU, can approach sustainability consistently. The application of the Envision/DNSH framework represents the first phase as a qualitative assessment of our method.

The need for an LCA cradle-to-gate/site analysis: the second phase of the method. The Envision/DNSH assessment tool that we proposed in the previous pages is needed in the first step of our methodology, and, as said, it creates the framework for the specific construction case. When defining the ratings for each indicator, following the Envision protocol rules, the decision maker has to move from the strategy's qualitative world to the tactics' quantitative world. For this to happen, a Life Cycle Assessment is needed, focused on the construction process's cradle-to-gate/site life cycle span.

Depending on the process, it can be relevant to set the boundaries at the 'gate' or at the 'site': even if the materials and product used may have central relevance in terms of impact when it comes to construction processes, the implementation in the site can create alternatives and make the difference. This is the case for ground improvement techniques, and this is the reason why, very often, a simple Environmental Product Declaration in itself does not make sense in measuring sustainability (while advertising tells our sector the contrary …), because it stops at the 'gate' of the site work.

Life cycle stage	Description	Module
Product stage	Raw material extraction and processing	A1
	Transport to the manufacturer	A2
	Manufacturing	A3
Construction process stage	Transport to the construction site	A4
	Construction	A5
Use stage	Use of the product	B1
	Maintenance	B2
	Repair	B3
	Replacement	B4
	Refurbishment	B5
	Operational energy use	B6
	Operational water use	B7
End-of-life stage	Demolition/Deconstruction	C1
	Demolition waste transport	C2
	Waste processing	C3
	Waste disposal	C4
Benefits and loads beyond the system	Reuse, Recovery, Recycling, Potential	D

Tab. 6-1, System boundaries according to EN 15804 and EN 15978, cradle-to-gate and cradle-to-site shaded in grey.

A full life cycle analysis performed for the whole project requires a significant set of modeling and a multidisciplinary set of design choices that make the full LCA a ‘difficult’ tool for holistic decisions for large construction (infrastructure) processes. When an LCA analysis is focused on a cradle-to-gate phase that isolates a specific construction process, it 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/site LCA analysis is the second phase of our methodology and is used to ground the rating for the Envision indicators and help maintain consistency in the sustainability approach to the project. Being connected through the framework to the EU taxonomy gives the quantitative feedback that the EU Regulation seeks.

Revising the Envision/DNSH assessment in the light of the LCA Analysis: the third phase of the method. Once the LCA analysis is completed a final revision of the assessment is made, and the valuation is finalized. The output of the three-phased method allows communication with the stakeholders at three levels. At the highest level, a single ‘score’ for the project can be the ideal project communication tool for non-specialized stakeholders; at the intermediate level, the indicators score can explain the reasons behind sustainability strategy and tactics in the project; at the extreme detail level, the LCA output can quantitatively (and transparently) support procurement decisions in the construction phase.

6.2 The case study: the analysis of three soil treatment ground improvement alternative strategies through the lenses of sustainability

For geotechnical engineering to contribute to sustainable development, the core practice must be made environmentally friendly and resource-efficient. However, geotechnics has to be able to tell how much it contributes. With their diversity and innovative variability of needs and technologies, ground improvement techniques are an ideal testing field for a sustainability-based design approach. On the one side, there is the need to focus on the efficiency of the processes and the technologies; on the other hand, there is a complex variety of materials involved. Geotechnics stakeholders (designers, constructors, customers) are often faced with ground improvement needs that are required to deal with many contextual constraints: logistical, mechanical, schedule, and cost. Furthermore, those are so compelling that there is no time to consider environmental efficiency (read sustainability) as a relevant criterion for a choice.

The approach presented in the thesis, which focuses on cradle-to-gate or cradle-to-site schemes and keeps the level of detail at the construction stage, allows the sustainability assessment to become extremely powerful in strategy selection and technology fine-tuning phases and, above all, easy to perform. This study aims to open the way to use life cycle thinking in geotechnics as an everyday tool that can make 'the' difference for decision-makers and designers.

To this aim, we designed an artificial case study where an open-air excavation below the water table (we assumed a typical soil pattern in the area of Milan) needs to be stabilized. Three soil improvement technologies/strategies are used: permeation grouting, jet grouting, and soil freezing. Both single- and double-fluid jet grouting techniques are explored, and both freezing methods, with brine and nitrogen as coolants, are compared. This makes five cases studied in total. The implementation of the three-phased method is aimed to show different ranks of impact and different fine-tuning and improvement options [Pettinaroli, Susani et al., 2023].

6.2.1 Soil treatment technologies usable for the pilot case

Infrastructure development mostly entails interventions within the earth's surface. During the execution of infrastructure projects, several challenges arise that necessitate the use of ground improvement technologies. These challenges encompass a range of difficulties, including foundation establishment, excavation, stabilization, landscape preservation, slide stabilization and protection, ground impermeabilization, and ground decontamination. However, it is worth noting that these challenges may be effectively addressed via the utilization of appropriate ground improvement techniques. These interventions can serve a temporary purpose by providing a beneficial effect solely during the construction phase, such as ensuring the stability of the ground or preventing water leakage during the excavation of a shaft or tunnel. Additionally, they also serve a long-term function that is essential for the lifespan of the infrastructure, such as reinforcing a structure or establishing an impermeable barrier beneath a dam. In the latter scenarios, it is anticipated that the treatment's impact would endure for an extended duration, including the lifespan of the infrastructure. Conversely, in the former scenarios, the influence may diminish rapidly after the conclusion of the building activities. Therefore, these interventions may have varying effects across the several stages of a Life Cycle Assessment (LCA), with minimal or no influence observed alone at the conclusion of the site stage.

This study primarily examined a specific category of soil treatment that involves the utilization of tiny diameter drilling technology for the execution of the treatment process. In more depth, the study encompassed an examination of three specific technologies: permeation grouting, jet grouting, and artificial ground freezing. The initial operational activity that must be performed on-site is the execution of drillings with a diameter ranging from 90 to 130 mm. This may be accomplished using a drilling machine of the same kind.

The actions that follow might vary significantly across different technologies in terms of equipment, materials, procedures, management of treatment activity, as well as the activities to be conducted during subsequent infrastructure building. Hence, these variations also result in diverse effects on the progress of work and the establishment of operational and maintenance procedures. Furthermore, various methodologies employed within a given technological domain provide distinct and noteworthy effects.

As a matter of fact, among our case studies, we distinguish:

- One permeation grouting application.
- Two different systems of jet grouting treatment:
  - the mono fluid system, using cement-based grout as operational fluid
  - the double fluid system, using also compressed air as operational fluid
- Two different systems of artificial ground freezing treatment:
  - the so-called closed system, using brine as coolant
  - the so-called open system, using liquid nitrogen as coolant

The following chart shows a conceptual scheme that points out the main common aspects and the principal differences between the technologies and their main variants considered in our study.

In addition to the drilling phase, the graphic highlights additional comparable elements that are commonly found in the examined technologies.

- The installation of pipes embedded with a cement grout is a necessary step in the implementation of permeation grouting and artificial ground freezing techniques.
- Both jet grouting and permeation grouting include the utilization of cement grouts in their respective procedures.
- All drilling procedures in soil result in the formation of a columnar element. The usual diameters of columns produced by jet grouting and permeation grouting have practical limits. However, the dimensions of columns created using artificial ground freezing increase endlessly as a function of the freezing period.

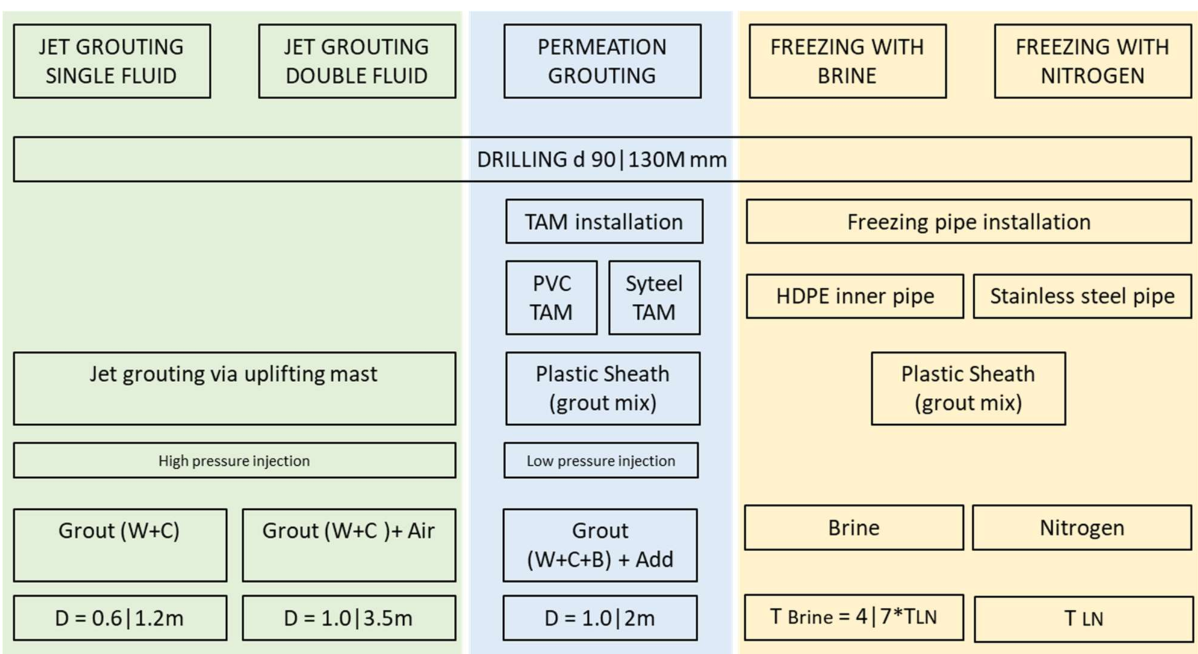


Figure 6-1, The main characteristics of the ground improvement technologies applied for the pilot case analysis.

In the next paragraphs a short description of each technology is given as an introduction to the following chapters.

6.2.1.1 Permeation grouting (PE)

This type of treatment aims to fill the soil's voids with a fluid injected using a low pressure to allow its spread into a specific ground volume, producing a negligible displacement between the soil grains. The fluid injected in the voids, according to its rheological behavior, hardens to a solid or gel, thus affecting the geotechnical and hydraulic properties of the injected soil.

In the case of the cement-based mixture (solid result), the treatment usually increases the mechanical properties (cohesion, stiffness) as well as the hydraulic properties (reduction of the permeability) of the treated soil.

The soil permeation grouting is carried out through sleeved pipes (also known as “tubes à manchettes” or TAM). Into the ground volume to be treated, these pipes are installed into boreholes with low diameters (usually Ø90÷120 mm), executed by a drilling unit, following proper procedures depending on the ground conditions and the drilling geometry (direction, length). To simplify the execution, it may be necessary to drill with a low quantity of fluid (water, cement grout, or polymeric-based fluid). To guarantee the borehole side stability, mainly if the soil fine grain percentage is very low, a metallic casing is used during the drilling, being removed after the TAM installation.

The TAM is embedded in the ground surrounded by a plastic cement based grout, that fixes the pipe in the soil and completely fills the annular space with a continuous, relatively soft material. The pipe is equipped with plastic valves (manchettes), having a defined interrexes along the tube (normally between 0,25 and 0,50 m, usually 0,33 m), in correspondence of 3÷4 ~Ø2mm holes made in the pipe wall at the same level.

The injection is carried out by inserting inside the TAM a double-packer (having a length similar to the sleeves interaxis) connected to an injection pump via a proper pipeline. Usually the packer is firstly placed at the level of the deeper manchette of the TAM; the o-rings placed at the packer extremities are expanded in order to isolate the injection chamber from the rest of the pipe. Then it is possible to start the injection, by pumping the grout via the packer.

The grout is injected at low pressure controlling the flow rate of the pump. The management of the process is based on the evaluation of these operational parameters as a function of the soil condition (granulometric composition, relative density, voids index) as well as of the working context (presence of structures or sensible obstacles, level of the sleeve, etc.). The injection is the carried out for each sleeve of a TAM, in all the TAMs installed in the ground.

Usually, the grout volume to be injected through a sleeve is pre-fixed (“controlled volume” method), as well as the fluid flow rate and the grouting pressure limitations. The exceeding of the latter is usually a sign of the achievement of the saturation degree of the soil for the grout mix injected; in this case, the injection is stopped, regardless of the volume target. Here comes the interesting part of the TAM technology: it is possible to proceed with the following stages by injecting progressively more permeating grout mixture, using the same procedure with proper referring parameters of limitation pressure flow rate and fluid quantity. Nowadays, the operating parameters (flow rate, pressure, injected grout volume) are controlled with an automatic unit equipped with software that allows the recording of the data and for the onsite operators to manage the process, aided by partial automation.

Several injection stages can be carried out, as previously pointed out. According to the target of the treatment, different kind of grouts as well as number of stage can be designed. The technology allow to evaluate the progress of the treatment, by an expert analysis of the operative parameters. The possibility to implement a multi-stage process, thanks to the repetitive use of the TAMs, allow to tailor the permeation grouting to any zone of the ground, making the technology very versatile.

In this study, the analyzed permeation grouting treatment is assumed to be efficiently carried out using only a cement-based grout, without the necessity of integrative stages of silica grout injection.

6.2.1.2 Jet grouting (JG)

This type of treatment is based on mixing the in situ soil with a cement-based mixture, producing a partial soil substitution to create mild concrete elements with improved mechanical and hydraulic characteristics concerning the natural ground conditions. The process has a spoil material, also composed of soil and cement grout, to be collected and disposed of..

The technology consists of the injection of a stabilizing mixture at very high pressure (30÷70 MPa) and through special nozzles. The nozzles (one or more) are installed at the top of the particular must of the drilling unit. After the drilling in the ground down to the required level, the must, rotating, is lifted according to a defined temporization of both movements. The grout ray, injected by the nozzles, breaks up the soil, and this effect, combined with the rotation of the must, produces the mixing of the cement grout and the soil in situ.

The result is to form a sort of conglomerate soil elements (the so called jet grouting column) that, once the setting time of the mixture has elapsed, owns improved mechanical and hydraulic characteristics compared to the initial conditions. The partial substitution of the ground in situ with the cement grout involves that a spoil material (also composed by grout and soil) shall be released in surface rising up through the drilling hole, during the injection process. Due to the mass balance principle, in case of absence of spoil, an uplift of the surface would occur; this phenomenon has to be carefully avoided, easing, during the jet grouting execution, a correct spoil releasing.

The amount of spoil varies from 80-100% of the treated ground (in cohesive soils) to 30- 50% in the case of coarse soils, where drainage effects take place.

With this technology, the soil can be improved mechanically to a high level and given a precise geometric shape. The shape's size depends on both the energy used for treatment and the properties of the soil. More changes are made to the mechanical properties of the jet-grouted soil than can be made with regular injections. To this end, a grout composed of water and cement with a W/C≈1 ratio is currently used.

This technology can be successfully used for treating a rather wide range of soil composition, also well-graded. It tends to lose its efficiency in the case of very permeable gravelly layers, where the grout tends to “run” far from the injection point. On the other hand, the more cohesive the soil, the less the breaking-up effect of the jet treatment.

Several methods have been created to increase the column size and even get different shapes for the jet grouted soil elements since the technology's effect is directly linked to the energy used during the injection.

For the latter aspect, different management of the mast rotation allows for obtaining, for instance, elliptical columns (applying a variable rotational speed to the mast), or so-called mono-directional treatment, in which no rotation is applied to the mast. The bit is equipped with two nozzles counterposed with an angle lower than 180° to obtain a “V-shaped” oriented element. This application will not be examined in this study, even though it can be assessed similarly to the columnar element execution process.

Following the energetic conception of the jet grouting treatment, the column diameter increases with the energy provided by the treatment. However, it decreases with the increment of the compaction degree and the relative density of the soil. While it seems to be still difficult, at state of the art, to correlate a univocal, measurable soil parameter to the obtainable jet grouting column diameter, the latter varies somewhat regularly with the treatment energy, which is directly proportional to the injection flow rate of the grout and, more smoothly, to the injection pressure.

To increase the diameter of the jet columns, a different technology has been set up that uses compressed air as a secondary fluid, which provides additional energy to contribute to the process and improves the efficiency of the treatment. It exists also a version that uses water as a third operational fluid, less diffused than the previous two.

In this study, the single fluid and double fluid system has been considered.

6.2.1.2.1 Single fluid system

The jet technology made with the sole cement grout allows the obtain of columns having diameter variables between 0,60 m and 1,20 m. In the case of clayey soils, the diameter can even be 0,50 m, but in this soil type, it is suggested to use the double fluid technology. The grout quantity injected in the ground is a combination of the grout flow rate pumped by the high-pressure pump and the uplift velocity of the mast with the nozzles, which is carried out by steps usually of 4 cm. An entire rotation of the mast has to be carried out in the time between two consecutive upshift steps. Mechanical properties are widely variable in function of the soil composition: for sandy layers, UCC test provides strengths that usually start from q=5 MPa up to values that increase with the complementary soil composition (from silt to gravel), between 15 to 30 MPa; for silts, the range varies from 2 MPa up to around 8-10 MPa, while for clays (with cu<50kPa) the values start from 1 MPa. The elastic modulus E is, on average, related to the UCC strength by the relation E~500*q. The permeability coefficient tends to achieve values between 0,5-1*10-7 m/s, tested with Lefranc test; in any case, the general homogeneity of the treatment governs the hydraulic behavior.

6.2.1.2.2 Double fluid system (JG-DF)

The jet technology uses the air as a secondary fluid to increase the energy of soil breaking up. The air is provided by an air compressor, with a pressure around 0,8~1,2 MP, a flow rate of 8-10 mc/min. The air flows along the drilling must into a duct coaxial to the grout one and is injected into the ground through a dedicated annular section that surrounds the circular grout nozzle. The process is then similar to the JG-SF system, except that the uplift speed and the grout flow rate are higher than in the previous case. As a result, the diameter achievable with the double fluid technology may vary from 1 m (in clayey soils) up to 3,5 m in medium-density sandy-gravelly soils. Mechanic and hydraulic parameters are similar to the values obtainable with the single fluid technique; sometimes, the strength results slightly lower because of the air inclusion in the treated soil, while hydraulically, this reduction is almost never observed, being the air bubbles isolated from each other. The double fluid system is very frequently used for the execution of bottom plugs for excavation under the water at ground level. At the same time, it is normally avoided for fore-poling canopy treatment in tunneling, where a single fluid is preferred. In other conditions, the system choice depends on the local conditions or constraints, the design concept, and the site organization.

6.2.1.3 Artificial ground freezing (AGF)

This type of treatment produces the freezing of the water included in the soil's pores, producing a treated volume composed of cooled natural soil and ice. The frozen body is hydraulically perfectly watertight and has improved mechanical properties than the natural soil in situ due to the mechanical properties of the ice and the bonding effect that the latter creates between soil grains.

The Artificial Ground Freezing technique requires the installation in the ground of special metallic freezing probes in which a fluid coolant circulates. The probes release the cryogenic energy by convection to the surrounding soil, which gradually gets cold until the pore water freezes at 0°C. The freezing process continues, creating a column of frozen soil around the probe. The process theoretically may have endless progress. In practice, several probes are disposed of according to a design geometry to form a frozen soil body. Thus, at a certain moment, the frozen soil columns merge each other, and after a transient, the frozen body tends to expand orthogonally to the probes' alignment. This first stage, called the freezing stage, allows for the creation of the frozen body. Then, the latter must be efficient for the entire duration of the work for which the treatment is necessary: for example, a tunnel excavation. So it starts the second phase, called the maintenance stage, during which the freezing process continues by maintaining the hydraulic and, if necessary, the mechanical functionality of the frozen soil. When the necessity of the functionality ceases, the process is stopped, and the soil heats up to the natural conditions.

Ground freezing, thus, is a thermal process. The treatment is based on providing energy for the extraction of calories from the ground. On the one side, there is the coolant, at a temperature strongly below 0°C, that circulates in the probes fed by a freezing plant to, which are connected via a circuit.

On the other side, there is the ground, composed by soil and water (that must be present at least with a saturation degree of 70%) at measurable temperature. The frozen soil body is created by a set of freezing pipes placed in the ground. The geometrical disposition is a function of the treatment purpose. The impervious frozen ground body is delimited by other impervious layers or walls, allowing the creation of a volume no longer affected by water inlets during the maintenance stage.

Each freezing lance is inserted in a borehole drilled in the same way as for a TAMs installation for the permeation grouting, including its embedment using a ternary cement-based grout for sealing the annular space between the hole and the probe, reducing thus the voids and water presence in the mass to freeze.

The probe is composed by two coaxial pipes:

- The external is plugged at the end in the ground and equipped with a special head for connecting to a feeding circuit.
- The special head is connected to the inner pipe allowing the circuit to feed it the coolant.
- The latter flows to the other open end of the inner pipe and then returns along the annular space up to the head, where another connection allows for the fluid to be outlined to a release circuit.

The fluid streaming carries out the freezing process, exchanging calories with the ground. The AGF process is controlled by monitoring the evolution of the temperature in the ground in real-time. For this purpose, additional pipes are installed beside the soil volume to be frozen, equipped with thermometric sensors connected by wire to an automatic unit that records the data practically in real-time and sends them to a dedicated platform. The latter is usually accessible via the internet by the process managers, who can control and evaluate the thermal condition ongoing in the soil and subsequently operate on the freezing plant in order to drive the treatment correctly as well as optimize the energy consumption.

6.2.1.3.1 Closed system AGF (with brine) - (AGF-BR)

This system uses, as a coolant, a calcium chloride liquid brine having a freezing point at around -50°C. From the freezing plant, the brine, having a temperature of -35°C, is pumped in the distribution circuit pipeline insulated with a proper material (armaflex), and it is delivered, via the special head described above, to each probe.

The inner pipes of the probes are made in HDPE, with a diameter that guarantees the same areal section as the annular space, to preserve a regular flow of the liquid brine in the probe. The brine gets back from the probe with a higher temperature: -27°÷-29°C during the energy-intensive freezing stage and around -31°÷-33°C during the maintenance stage. The brine flows back to the freezing plant, where it is chilled down to -35°C by an ammonia circuit that operates with the aid of a cooling tower.

The freezing plant operates continuously during the artificial ground freezing process, fed by electric energy: high absorption during the freezing stage and reduced absorption during the maintenance stage. The initial freezing stage requires several weeks (usually from 5 to 7, but even more, depending on the geometry as well as on the ground nature) for the creation of a freezing body.

6.2.1.3.2 Opens system AGF (with liquid nitrogen) (AGF-LN)

The system uses as coolant the Liquid Nitrogen, stored in tanks at a pressure of 2÷3 bar at -196°C of temperature. The LN is introduced into the distribution circuit (made by insulated, stainless pipes) and then delivered to each probe via the insulated, stainless, special head. The LN flows through the inner metallic pipe that has a small diameter (20-22 mm). During the streaming, the LN rapidly exceeds the evaporation temperature and changes of state; in this stage, the energy consumption is very high, and being to a very low temperature, this produces a cryogenic thermal shock that freezes quickly the ground surrounding the probe. The gaseous nitrogen flows then along the annular section back to the probe head and from there to the discharge circuit, whose final stretch is a chimney that releases the gas to the free air. The change of state of the nitrogen takes place initially in the first part of the probe, near the head, and then "moves" gradually to the end of the inner pipe.

The open circuit process requires a constant refill, by tank trucks, of the storage tanks that generally have to be installed at the site. In case of a small freezing circuit, it is possible to connect the latter directly to the tank truck without installing insulated silos.

The initial freezing stage, using the LN, is quick, requiring usually 7÷10 days, depending on the ground volume to be frozen. Temperature monitoring is, in this case, even more crucial than with the AGF-BR method because the freezing process is definitely more rapid, and the LN cost may rise dramatically in case of bad management of the process. The maintenance stage is carried out intermittently by feeding the circuit with LN for 10-15 hours, with a quick drop of the temperature in the soil, followed by a stopping period of 2÷3 days, during which no LN feeding is ongoing, while the main works can take place. During the stopping period, the cryogenic energy migrates from the zone closer to the probes to the periphery, guaranteeing the maintenance of the necessary thickness of the frozen soil body.

6.2.2 Applying the Envision/DNSH framework to ground improvement construction processes

The Envision/DNSH framework developed in the previous chapter can be simplified to the case of geotechnical construction processes by avoiding those indicators that involve more general aspects of the infrastructure design (plans, strategic documents, etc.) and keeping the focus on the construction process in itself.

The following table represents this reduces framework and will be used in the analyses. Essentially, few indicators have been avoided:

- QL1.2 Enhance Public Health & Safety
- QL1.3 Improve Construction Safety
- QL1.5 Minimize Light Pollution
- LD2.1 Establish a Sustainability Management Plan
- NW2.2 Manage Stormwater
- CR2.5 Maximize Resilience

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**	Biodoversity 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	-
	Maximun achievable rating	232						

Tab. 6-2, Reduced frame Envision vs. DNSH for ground improvement techniques.

6.2.3 The case study

Grouting techniques involve the low pressure (10-20 bars) injection in the ground of a pumpable slurry or grout., When the injection fills the voids between the soil particles without appreciable displacement of the surrounding material, the process is referred to as permeation grouting. The result is a strengthens of the soil mass and/or a reduction of its permeability. The design of the fluid mix is, mainly, cement based with specific additives, depending on the characteristics of the soil to be improved. The fluid is pumped in the soil through PVC sleeved pipes (tubes à manchette, TAM).

Jet grouting technique involves the injection with high pressure (400-600 bars, hence the term "jet") of a ray of water-cement grout by nozzles on a rotating, uplifting, drilling rig. The process causes the soil disintegration and its substitution with a mix of grout and soil producing a column of "jet grouted" ground, and the release in surface, via the drilling hole, of a spoil material (again soil and grout).

Finally, and with a completely different approach, when the soil is wet and below the water table, it is possible to freeze provisionally the groundwater: the ice bonds the soil particles creating or increasing the cohesion and improving the mechanical behavior of the frozen ground as well as making the latter watertight; y; this process is referred to as ground freezing, and can be obtained by the soil with metallic probes embedded in it, in which circulates a coolant , for example a brine or liquid nitrogen. The pipes transfer frigories to the surrounding ground freezing the soil and creating a stable 'frozen wall'.

As an ideal design case study for the application of the Three Phased Method for ground improvement treatments, an excavation site located in the municipality of Rozzano (MI) was considered. The choice of the location is based on the knowledge of the area deriving to the authors from previous interventions designed by the same authors, which provided the geological and hydrogeological information necessary for the classification of the area and the modeling of a plausible scenario.

The excavation site is assumed to have the following characteristics:

- square shape with sides of 10 meters each;
- depth of 5 meters, with the following stratigraphy:
    - 5 m of gravel and sandy layer
    - watertable level at -1m
    - from -5m clayey formation;
- negligible groundwater speed.

These assumptions guarantee important advantages;

- the simple excavation geometry makes calculations easier;
- the granulometric composition of the soil to be excavated and the negligible underground water flow do not preclude the use of any of the soil treatment methods described in the previous paragraphs;
- the watertightness nature of the layer of clay at the level of the excavation bottom avoides any problem piping , which could cause flooding of the site.

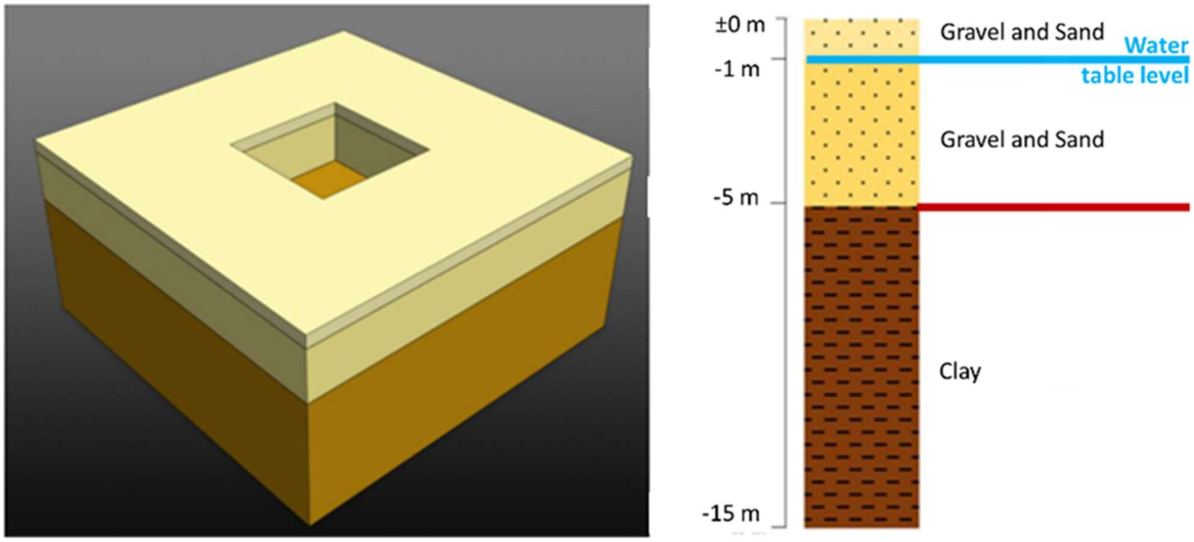


Fig. 6-2, The open-air excavation for the case study [Pettinaroli, Susani et al., 2023].

As said, thanks to the geometry of the excavation case, to make our analyses comparable the treatment has been designed in such a way that the different techniques use a similar modular pattern of 'columns' and drilling depths; this allows the sustainability analysis to focus on what is relevant under the environmental impact point of view.

7 The first phase of the method: Assessing sustainability qualitatively

7.1 Qualitative application of the framework and sustainability rating of the techniques.

As a first step, we apply the framework combining Envision and DNSH to this ideal case, as developed in the previous chapter.

Being our case a design experiment, those indicators that depend on the community and landscape context of a 'true' case 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/limitations of the technologies and depending on the expected results from the LCA analysis and the related sensitivity runs. After the numerical analysis, the values assigned to the Envision indicators will be refined in phase three.

The following table gives a detailed overview of the selected credits for the Envision framework adapted to ground improvement techniques.

INDICATOR (CREDIT)	SECTION	METRIC	MAX SCORE
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.	12
QL1.6 Minimize Construction Impacts	QUALITY OF LIFE: WELLBEING	Extent of issues addressed through construction management plans.	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.	18
LD3.3 Conduct a Life-Cycle Economic Evaluation	LEADERSHIP: ECONOMY	The comprehensiveness of the economic analyses used to determine the net impacts of the project, and their use in assessing alternatives to inform decision making.	14
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.	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.	16
RA1.4 Reduce Construction Waste	RESOURCE ALLOCATION: MATERIALS	Percentage of total waste diverted from disposal.	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.	12
RA2.3 Use Renewable Energy	RESOURCE ALLOCATION: ENERGY	Extent to which renewable energy sources are incorporated.	24
RA3.3 Reduce Construction Water Consumption	RESOURCE ALLOCATION: WATER	The number of strategies implemented during construction that reduce potable water consumption.	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.	20
NW3.5 Protect Soil Health	NATURAL WORLD: ECOLOGY	Degree to which the disruption of soil health has been minimized and restored.	8
CR1.1 Reduce Net Embodied Carbon	CLIMATE AND RESILIENCE: EMISSIONS	Percentage of reduction in net embodied carbon of materials.	20
CR1.2 Reduce Greenhouse Gas Emissions	CLIMATE AND RESILIENCE: EMISSIONS	Percentage of reduction in operational greenhouse gas emissions.	26
CR1.3 Reduce Air Pollutant Emissions	CLIMATE AND RESILIENCE: EMISSIONS	Reduction of air pollutants compared to baseline.	18
			232

Tab. 7-1, The Envision/DNSH framework evaluation for the case study, maximum available scores.

In the following paragraph each of the five techniques is 'qualitatively' assessed with this tool following the procedure dedicated to the Envision SP certified by the Institute for Sustainable Infrastructure[2].

[2] One of the authors of this research (Stefano Susani) is a certified Envision SP professional. For more details about this credentialling process, please see: https://sustainableinfrastructure.org/credentialing/envision-sustainability-professional-env-sp/

7.2 Qualitative assessment for the permeation grouting technique

The qualitative scoring (first phase of the three-phased method) is 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.

The table and the radar diagram below summarize the ratings, and the radar diagram shows how the best ratings tend to be focused on resource allocation, climate, and resilience.

In the table, for each indicator, the column 'Criteria' explains the target set for the technique based on 'state of the art' knowledge and the case study design characteristics. Each indicator is analyzed in detail in the third phase, and the criteria of choice are assessed and evaluated based on the modeling outcome.

What is essential to notice, going through the criteria set by the protocol, is the fact that the achievement is related to several specific and concrete strategies/implementations that need to be taken into consideration during the development of the design (and as commitments for the following construction phase). Thanks to the fact that the protocol has a holistic view of the project, applying this approach to a construction process enhances the sustainability potential of the specific technique.

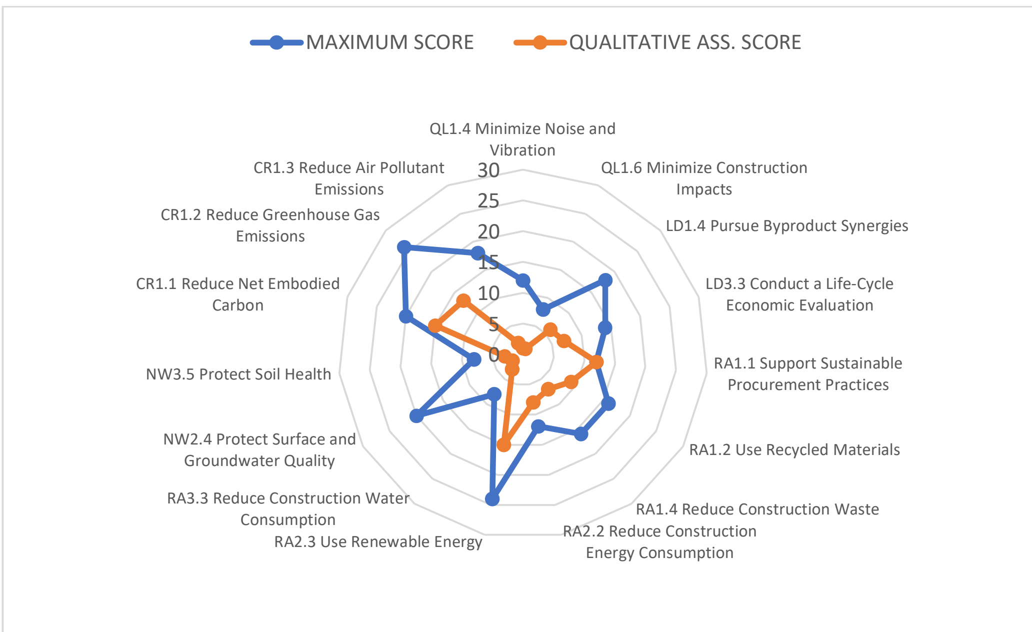


Fig. 7-1, Permeation grouting technique. Diagram of score contribution vs. each Envision indicator (Maximum achievable and qualitative score).

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. 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 project team demonstrates an active attempt to incorporate at least one byproduct synergy or reuse into the project.**	6	33%	18
LD3.3 Conduct a Life-Cycle Economic Evaluation	LEADERSHIP: ECONOMY	The comprehensiveness of the economic analyses used to determine the net impacts of the project, and their use in assessing alternatives to inform decision making.	LCCA is used to compare and assess **alternatives for at least one major design component**.	7	50%	14
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 50%** 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. Diversion may be a combination of waste-reduction measures and sourcing waste to other facilities for recycling or reuse.	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 ALLOCATION: 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 Consumption	RESOURCE ALLOCATION: WATER	The number of strategies implemented during construction that reduce potable water consumption.	At least **three (3) potable water conservation strategies** are 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, including temperature, during construction and operations. (II) The project includes spill and leak diversion systems, spill prevention plans, and cleanup. **The project does not create new direct pathways for surface water and/or groundwater contamination** such as: (a) Direct runoff into karst terrain; (b) · Untreated industrial or chemical discharge to	2	10%	20

INDICATOR (CREDIT)	SECTION	METRIC	CRITERIA	SCORE	%	MAX
			unlined industrial ponds or lakes; (c) · Reinjection water wells unless water is treated to secondary levels, or local regulations, whichever is more stringent; (d) or· Chemical, byproduct, or fracking water, injection.			
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 30% reduction** in total embodied carbon of materials over the life of the project compared to the baseline. Calculations should be in tons CO2.	15	75%	20
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 CO2e over the operational life of the project compared to the baseline. Calculations should be in tons CO2e. (II) The project team maps and calculates the total annual greenhouse gas emissions of the final project design for reporting purposes. This includes direct and indirect greenhouse gas emissions and sequestration associated with project operations. Calculations must be in CO2e.	13	50%	26
CR1.3 Reduce Air Pollutant Emissions	CLIMATE AND RESILIENCE: EMISSIONS	Reduction of air pollutants ompared 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
				104	45%	232

Tab. 7-2, Permeation Grouting Technique - The Envision/DNSH framework evaluation for the case study, assigned scores and maximum available scores.

The indicators that scored more than 50% of the maximum admitted total are:

- LD3.3 Conduct a Life-Cycle Economic Evaluation (50%).
- RA1.1 Support Sustainable Procurement Practices (100%).
- RA1.2 Use Recycled Materials (56%).
- RA2.2 Reduce Construction Energy Consumption (67%).
- RA2.3 Use Renewable Energy (63%).
- CR1.1 Reduce Net Embodied Carbon (75%).
- CR1.2 Reduce Greenhouse Gas Emissions (69%).

The indicators that scored between 20% and 49% of the maximum admitted total are:

- LD1.4 Pursue Byproduct Synergies (33%).
- RA1.4 Reduce Construction Waste (44%).
- RA3.3 Reduce Construction Water Consumption (38%).
- NW3.5 Protect Soil Health (38%).

The indicators that scored less than 19% of the maximum admitted total are:

- QL1.4 Minimize Noise and Vibration (8%).
- QL1.6 Minimize Construction Impacts (13%).
- NW2.4 Protect Surface and Groundwater Quality (10%).
- CR1.3 Reduce Air Pollutant Emissions (11%).

Compared to a maximum reachable of 232 points, this ground improvement process scored 107 points (which means an overall value of 47%). When confirmed by the analyses, this could be considered a good scoring (rewardable with a ‘gold’ rating following Envision rating scale).

7.3 Qualitative assessment for the single fluid jet grouting technique

The qualitative assessment of the Envision scoring for the single fluid jet grouting technique involves considering the project's characteristics, the five threshold requirements outlined in the Envision protocol, and an initial hypothesis regarding the potential impact performance of the permeation grouting soil treatment.

The following synthesis of ratings is shown in the table and radar diagram. The radar diagram illustrates that the highest ratings are predominantly centered around resource allocation, climate, and resilience.

Within the provided table, the column labeled 'Criteria' elucidates the predetermined objective for the approach, with respect to the current knowledge in the field and the specific characteristics of the case study design. In the third step, a comprehensive analysis is conducted on each indicator, with a focus on examining the criteria of choice and evaluating them based on the conclusion of the modeling process.

It is important to observe, while examining the criteria established by the protocol, that the attainment is connected to a number of distinct and tangible strategies/implementation that need careful study. The comprehensive perspective of the protocol contributes to the increased sustainability potential of the specific building technology by considering the project as a whole.

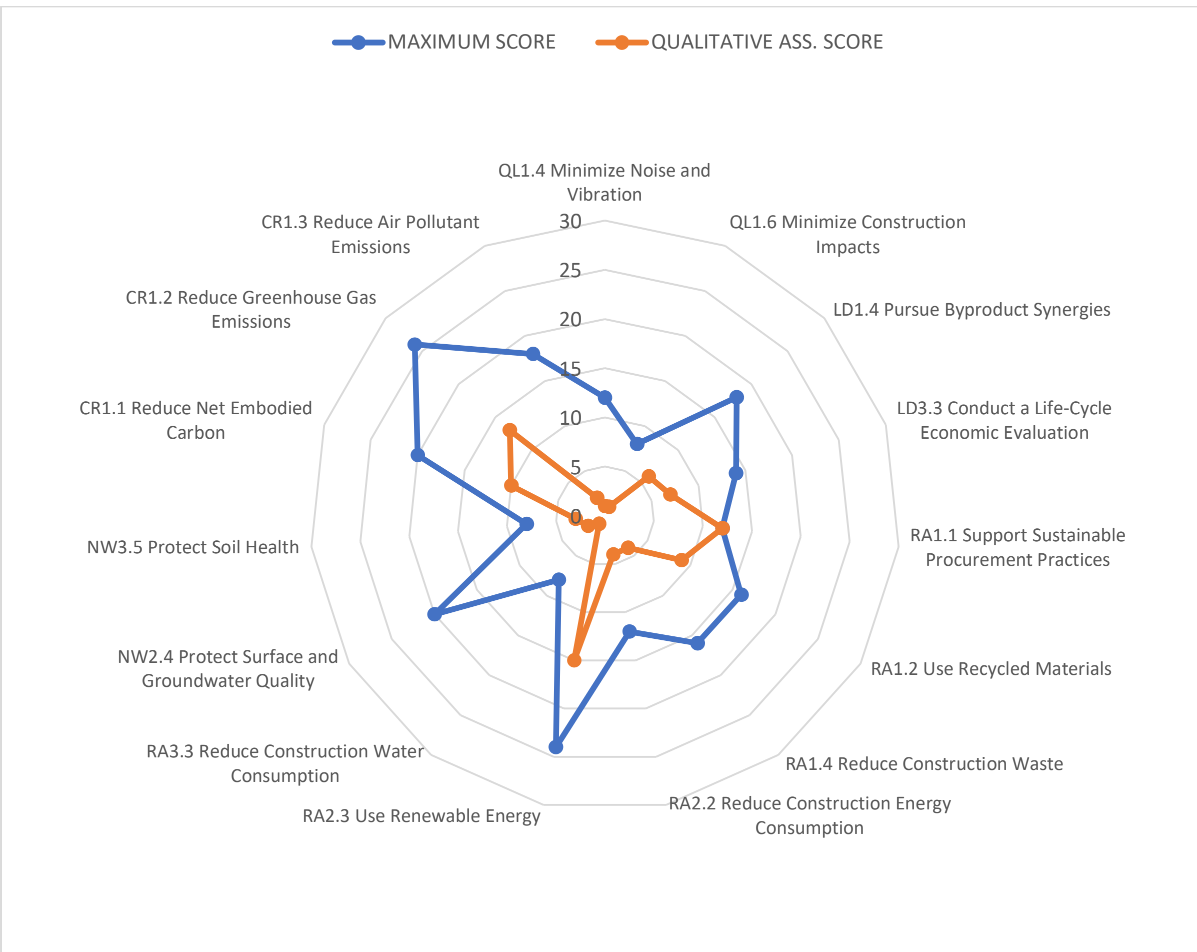


Fig. 7-2, Single fluid Jet Grouting technique - Diagram of score contribution vs. each Envision indicator.

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.	The project team demonstrates an active attempt to incorporate **at least one byproduct synergy** or reuse into the project.	6	33%	18
LD3.3 Conduct a Life-Cycle Economic Evaluation	LEADERSHIP: ECONOMY	The comprehensiveness of the economic analyses used to determine the net impacts of the project, and their use in assessing alternatives to inform decision making.	LCCA is used to compare and assess alternatives for **at least one major design component**.	7	50%	14
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 50% 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.	Implement a construction waste management plan that, at a minimum, identifies the materials to be diverted from disposal and whether the materials will be sorted on site or commingled. During construction **at least 25% of waste materials are recycled, reused, and/or salvaged**. Diversion may be a combination of waste-reduction measures and sourcing waste to other facilities for recycling or reuse.	4	25%	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 two (2) energy reduction strategies**.	4	33%	12
RA2.3 Use Renewable Energy	RESOURCE ALLOCATION: 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 Consumption	RESOURCE ALLOCATION: WATER	The number of strategies implemented during construction that reduce potable water consumption.	The project team conducts one or more planning reviews to identify and analyze options for reducing water consumption during construction. **At least one (1) potable water conservation strategy is implemented**.	1	13%	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, including temperature, during construction and operations. (II) The project includes spill and leak diversion systems, spill prevention plans, and cleanup. The project does not create new direct pathways for surface water and/or groundwater contamination such as: (i) Direct runoff into karst terrain; (ii) Untreated industrial or chemical discharge to unlined industrial ponds or lakes; (iii) Reinjection water wells	2	10%	20

INDICATOR (CREDIT)	SECTION	METRIC	CRITERIA	SCORE	%	MAX
			unless water is treated to secondary levels, or local regulations, whichever is more stringent; or Chemical, byproduct, or fracking water, injection.			
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.	Embodied carbon is calculated, or acquired by a validated source. Calculations include: Embodied carbon of production, including raw material extraction, refinement, and manufacture. Embodied carbon of transporting materials to the project site. The replacement, repair, or refurbishment of materials over the life of the project. 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. Calculations should be in tons CO2.	10	50%	20
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 CO2e*** over the operational life of the project compared to the baseline. Calculations should be in tons CO2e. (II) The project team maps and calculates the total annual greenhouse gas emissions of the final project design for reporting purposes. This includes direct and indirect greenhouse gas emissions and sequestration associated with project operations. Calculations must be in CO2e.	13	50%	26
CR1.3 Reduce Air Pollutant Emissions	CLIMATE AND RESILIENCE: EMISSIONS	Reduction of air pollutants ompared 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
				90	39%	232

Tab. 7-3, Single Fluid Jet Grouting technique - The Envision/DNSH framework evaluation for the case study, assigned scores and maximum available scores.

The indicators that scored more than 50% of the maximum admitted total are:

- LD3.3 Conduct a Life-Cycle Economic Evaluation (50%).
- RA1.1 Support Sustainable Procurement Practices (100%).
- RA1.2 Use Recycled Materials (56%).
- RA2.3 Use Renewable Energy (63%).
- CR1.1 Reduce Net Embodied Carbon (50%).
- CR1.2 Reduce Greenhouse Gas Emissions (50%).

The indicators that scored between 20% and 49% of the maximum admitted total are:

- LD1.4 Pursue Byproduct Synergies (33%).
- RA1.4 Reduce Construction Waste (25%).
- RA2.2 Reduce Construction Energy Consumption (33%).
- NW3.5 Protect Soil Health (38%).

The indicators that scored less than 19% of the maximum admitted total are:

- QL1.4 Minimize Noise and Vibration (8%).
- QL1.6 Minimize Construction Impacts (13%).
- NW2.4 Protect Surface and Groundwater Quality (10%).
- CR1.3 Reduce Air Pollutant Emissions (11%).
- RA3.3 Reduce Construction Water Consumption (13%).

Compared to a maximum reachable of 232 points, this ground improvement process scored 90 points (which means an overall value of 39%). When confirmed by the analyses, this could be considered a good scoring (rewardable with a ‘silver’ rating following Envision rating scale).

7.4 Qualitative assessment for the double fluid jet grouting technique

The initial evaluation of the Envision scoring for the double fluid jet grouting technique involves considering the project's characteristics, the five threshold requirements outlined in the Envision protocol, and an initial hypothesis regarding the potential impact performance of the permeation grouting soil treatment. The provided table and radar diagram offer a comprehensive overview of the ratings, with the radar graphic specifically highlighting the concentration of top ratings in the domains of resource allocation and climate and resilience.

Within the provided table, the column labeled 'Criteria' elucidates the predetermined objective for the approach, with respect to both the current knowledge in the field and the specific characteristics of the case study design. In the third phase, a comprehensive analysis of each indicator is conducted, with a focus on examining the criteria of choice and evaluating them based on the outcomes of the modeling process.

It is noteworthy to observe, when reviewing the criteria outlined in the protocol, that the attainment is contingent upon a variety of distinct and tangible strategies/implementation measures that want careful attention. The comprehensive perspective of the protocol contributes to the improved sustainability potential of the particular building process by applying this strategy.

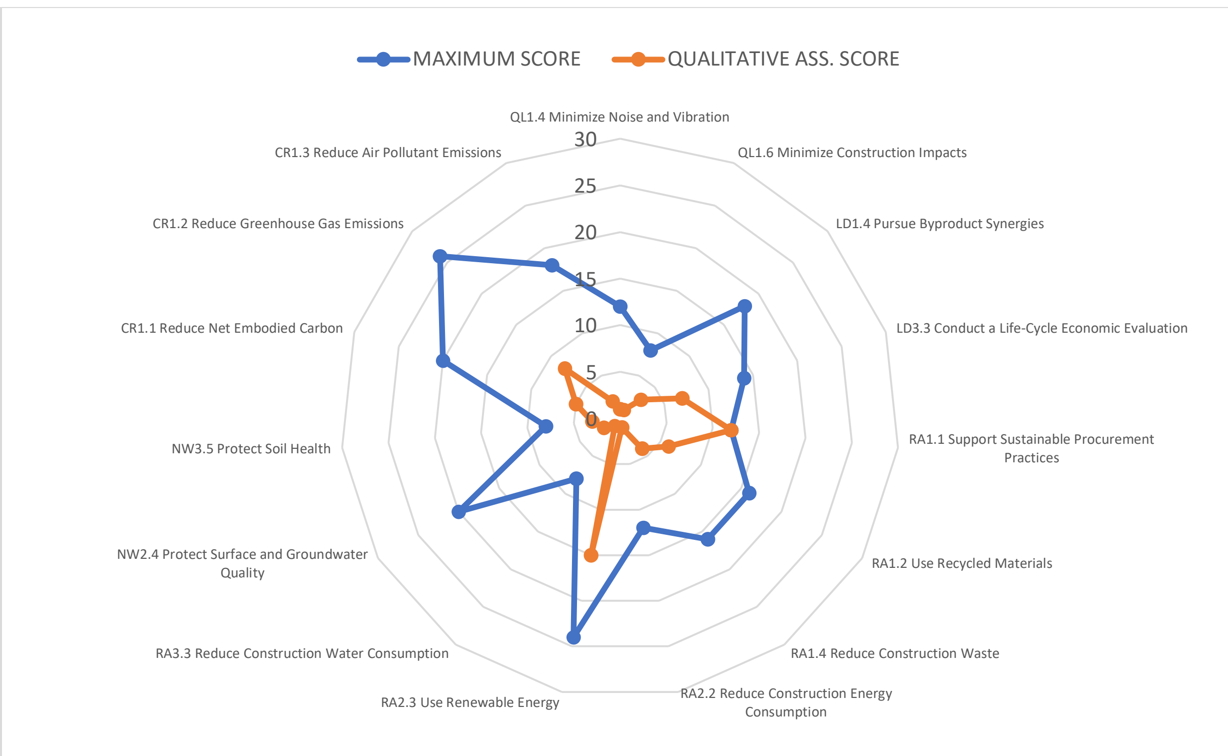


Fig. 7-3, Double fluid Jet Grouting technique - Diagram of score contribution vs. each Envision indicator.

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.	The project team **conducts an assessment of the availability and viability** of excess resources (i.e., waste) or capacity, including but not limited to waste materials, heating or cooling, financial capacity, land area/space, or management/personnel capacity.	3	17%	18
LD3.3 Conduct a Life-Cycle Economic Evaluation	LEADERSHIP: ECONOMY	The comprehensiveness of the economic analyses used to determine the net impacts of the project, and their use in assessing alternatives to inform decision making.	LCCA is used to compare and assess alternatives for **at least one major design component**.	7	50%	14
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 50% 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 15% (by weight, volume, or cost) of recycled materials** including materials with recycled content and/or reused existing structures or materials.	6	38%	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**. Diversion may be a combination of waste-reduction measures and sourcing waste to other facilities for recycling or reuse.	4	25%	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 team conducts one or more **planning reviews** to identify and analyze options for reducing energy consumption during construction.	1	8%	12
RA2.3 Use Renewable Energy	RESOURCE ALLOCATION: 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 Consumption	RESOURCE ALLOCATION: WATER	The number of strategies implemented during construction that reduce potable water consumption.	**At least one (1) potable water conservation strategy** is implemented.	1	13%	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, including temperature, during construction and operations. (II) The project includes spill and leak diversion systems, spill prevention plans, and cleanup. The project does not create new direct pathways for surface water and/or groundwater contamination such as: (a) Direct runoff into karst terrain; (b) · Untreated industrial or chemical discharge to unlined industrial ponds or lakes; (c) · Reinjection water wells unless water is treated to secondary levels, or local regulations, whichever is more stringent; (d) or· Chemical, byproduct, or fracking water, injection.	2	10%	20

INDICATOR (CREDIT)	SECTION	METRIC	CRITERIA	SCORE	%	MAX
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. Calculations should be in tons CO2.	5	25%	20
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 10% reduction in total CO2e** over the operational life of the project compared to the baseline. Calculations should be in tons CO2e. (II) The project team maps and calculates the total annual greenhouse gas emissions of the final project design for reporting purposes. This includes direct and indirect greenhouse gas emissions and sequestration associated with project operations. Calculations must be in CO2e."	8	31%	26
CR1.3 Reduce Air Pollutant Emissions	CLIMATE AND RESILIENCE: EMISSIONS	Reduction of air pollutants ompared 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
				71	31%	232

Tab. 7-4, Double Fluid Jet Grouting technique - The Envision/DNSH framework evaluation for the case study, assigned scores and maximum available scores.

The indicators that scored more than 50% of the maximum admitted total are:

- LD3.3 Conduct a Life-Cycle Economic Evaluation (50%).
- RA1.1 Support Sustainable Procurement Practices (100%).
- RA2.3 Use Renewable Energy (63%).

The indicators that scored between 20% and 49% of the maximum admitted total are:

- RA1.2 Use Recycled Materials (38%).
- RA1.4 Reduce Construction Waste (25%).
- NW3.5 Protect Soil Health (38%).
- CR1.1 Reduce Net Embodied Carbon (25%).
- CR1.2 Reduce Greenhouse Gas Emissions (31%).

The indicators that scored less than 19% of the maximum admitted total are:

- LD1.4 Pursue Byproduct Synergies (17%).
- QL1.4 Minimize Noise and Vibration (8%).
- QL1.6 Minimize Construction Impacts (13%).
- RA2.2 Reduce Construction Energy Consumption (8%).
- RA3.3 Reduce Construction Water Consumption (13%).
- NW2.4 Protect Surface and Groundwater Quality (10%).
- CR1.3 Reduce Air Pollutant Emissions (11%).

Compared to a maximum reachable of 232 points, this ground improvement process scored 71 points (which means an overall value of 31%). When confirmed by the analyses, this could be considered a good scoring (rewardable with a ‘silver’ rating following Envision rating scale).

7.5 Qualitative assessment for the brine ground freezing technique

In this scenario, the strategy for bettering the earth entirely shifts, and we begin working on freezing the ground instead. On the basis of the features of the project, the five threshold requirements indicated in the Envision protocol, and a preliminary hypothesis about the possible effect performance of the permeation grouting soil treatment, the qualitative (first trial) portion of the Envision scoring is assigned. This portion of the scoring is referred to as the envision score. A summary of the ratings can be seen below in the table as well as in the radar diagram. The radar diagram, in particular, demonstrates how the highest ratings are often concentrated in the areas of resource allocation as well as climate and resilience.

In the table, the column labeled "Criteria" provides an explanation of the target that was established for the technique based on the knowledge of the "state of the art" as well as the features of the case study design. During the third phase, each indication is subjected to a comprehensive analysis, and the criteria of choice are examined and appraised based on the conclusion of the modeling.

When going through the standards that have been established by the protocol, one thing that is essential to keep in mind is the fact that the accomplishment is connected to a variety of particular and concrete strategies and implementations that have to be taken into account. The use of this strategy to a building process elevates the specific method's capacity for promoting environmental sustainability. This is made possible by the fact that the protocol takes a holistic perspective of the project.

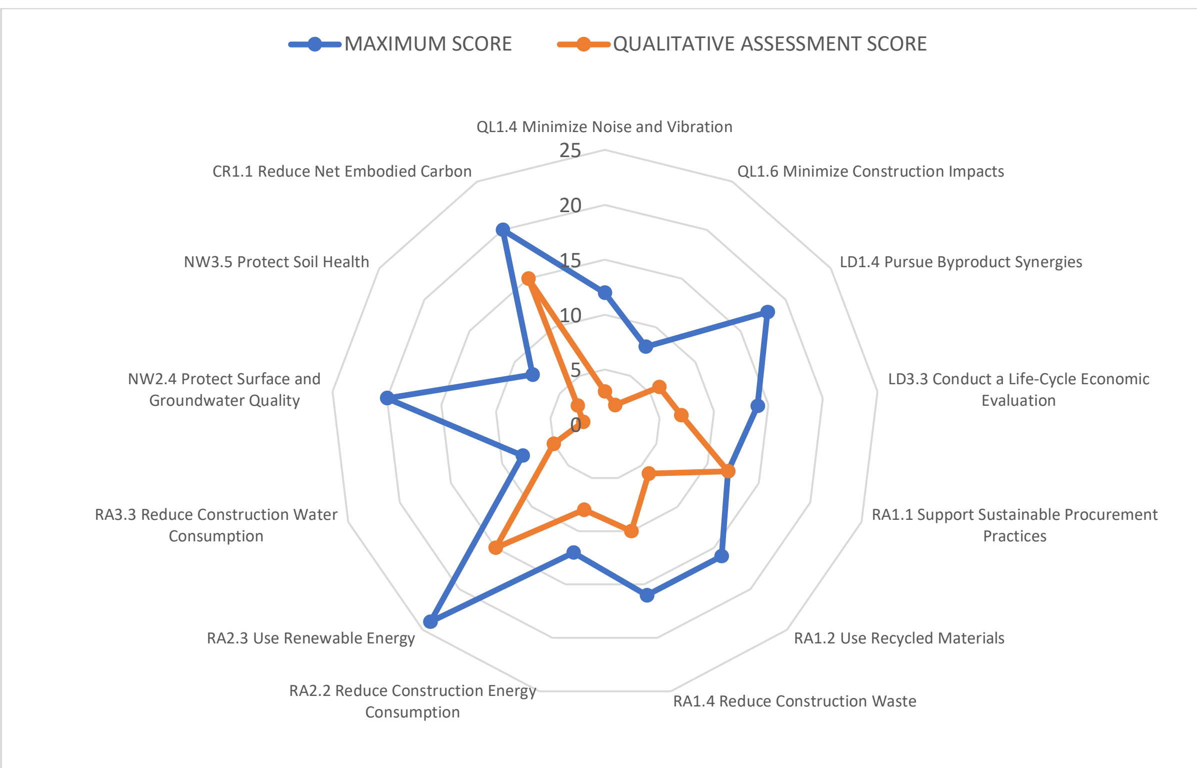


Fig. 7-4, Brine Ground Freezing technique - Diagram of score contribution vs. each Envision indicator.

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.	**Strategies are implemented to mitigate noise and/or vibrations during operations**. Noise reduction follows a mitigation hierarchy of avoidance/source elimination, minimization, abatement/receiver reduction, and offsetting/compensation.	3	25%	12
QL1.6 Minimize ConstructionI mpacts	QUALITY OF LIFE: WELLBEING	Extent of issues addressed through construction management plans.	The management plan addresses **one (1) type of construction impact**: noise, safety/ wayfinding, access/ mobility, or lighting,	2	25%	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. 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 project team demonstrates an active attempt to incorporate **at least one byproduct synergy or reuse** into the project.	6	33%	18
LD3.3 Conduct a Life-Cycle Economic Evaluation	LEADERSHIP: ECONOMY	The comprehensiveness of the economic analyses used to determine the net impacts of the project, and their use in assessing alternatives to inform decision making.	LCCA is used to compare and assess alternatives for **at least one major design component**.	7	50%	14
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 50% 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 15% (by weight, volume, or cost) of recycled materials** including materials with recycled content and/or reused existing structures or materials.	6	38%	16
RA1.4 Reduce Construction Waste	RESOURCE ALLOCATION: MATERIALS	Percentage of total waste diverted from disposal.	**At least 75% of all project materials, supplies, and equipment** meet the sustainable procurement policy/program requirements.	10	63%	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 ALLOCATION: 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 Consumption	RESOURCE ALLOCATION: WATER	The number of strategies implemented during construction that reduce potable water consumption.	**At least five (5) potable water conservation strategies** are implemented.	5	63%	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.	**Designs, plans, and programs** instituted to prevent and monitor surface water and groundwater contamination during construction and operations.	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	3	38%	8

INDICATOR (CREDIT)	SECTION	METRIC	CRITERIA	SCORE	%	MAX
			appropriate soil type, structure, and function to support healthy plant and tree growth.			
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. Calculations should be in tons CO_2.	15	75%	20
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 50% 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. This includes direct and indirect greenhouse gas emissions and sequestration associated with project operations. Calculations must be in CO_2e.	18	69%	26
CR1.3 Reduce Air Pollutant Emissions	CLIMATE AND RESILIENCE: EMISSIONS	Reduction of air pollutants ompared 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
				114	49%	232

Tab. 7-5, Ground Freezing with Brine technique - The Envision/DNSH framework evaluation for the case study, assigned scores and maximum available scores.

The indicators that scored more than 50% of the maximum admitted total are:

- LD3.3 Conduct a Life-Cycle Economic Evaluation (50%).
- RA1.1 Support Sustainable Procurement Practices (100%).
- RA1.4 Reduce Construction Waste (63%).
- RA2.2 Reduce Construction Energy Consumption (67%).
- RA2.3 Use Renewable Energy (63%).
- RA3.3 Reduce Construction Water Consumption (63%).
- CR1.1 Reduce Net Embodied Carbon (75%).
- CR1.2 Reduce Greenhouse Gas Emissions (69%).

The indicators that scored between 20% and 49% of the maximum admitted total are:

- QL1.4 Minimize Noise and Vibration (25%).
- QL1.6 Minimize Construction Impacts (25%).
- LD1.4 Pursue Byproduct Synergies (33%).
- RA1.2 Use Recycled Materials (38%).
- NW3.5 Protect Soil Health (38%).

The indicators that scored less than 19% of the maximum admitted total are:

- NW2.4 Protect Surface and Groundwater Quality (10%).
- CR1.3 Reduce Air Pollutant Emissions (11%).

Compared to a maximum reachable of 232 points, this ground improvement process scored 114 points (which means an overall value of 49%). When confirmed by the analyses, this could be considered a good scoring (rewardable with a ‘gold’ rating following Envision rating scale).

7.6 Qualitative assessment for the nitrogen ground freezing technique

For nitrogen-based freezing, the qualitative (first trial) of the Envision scoring is based on project characteristics, the five threshold requirements in the protocol, and a preliminary hypothesis about the permeation grouting soil treatment's impact performance. The table and radar diagram below summarize the ratings, and the radar graphic demonstrates how resource allocation and climate and resilience receive the highest scores.

The column 'Criteria' in the table for each indicator describes the technique's target set based on 'state of the art' knowledge and case study design features. In the third step, each indication is examined and the criterion of choice evaluated based on the modelling outcome.

It's vital to note that the protocol's requirements require a number of particular and precise strategies/implementations to achieve success. Because the protocol takes a comprehensive picture of the project, applying it to a building process increases its sustainability.

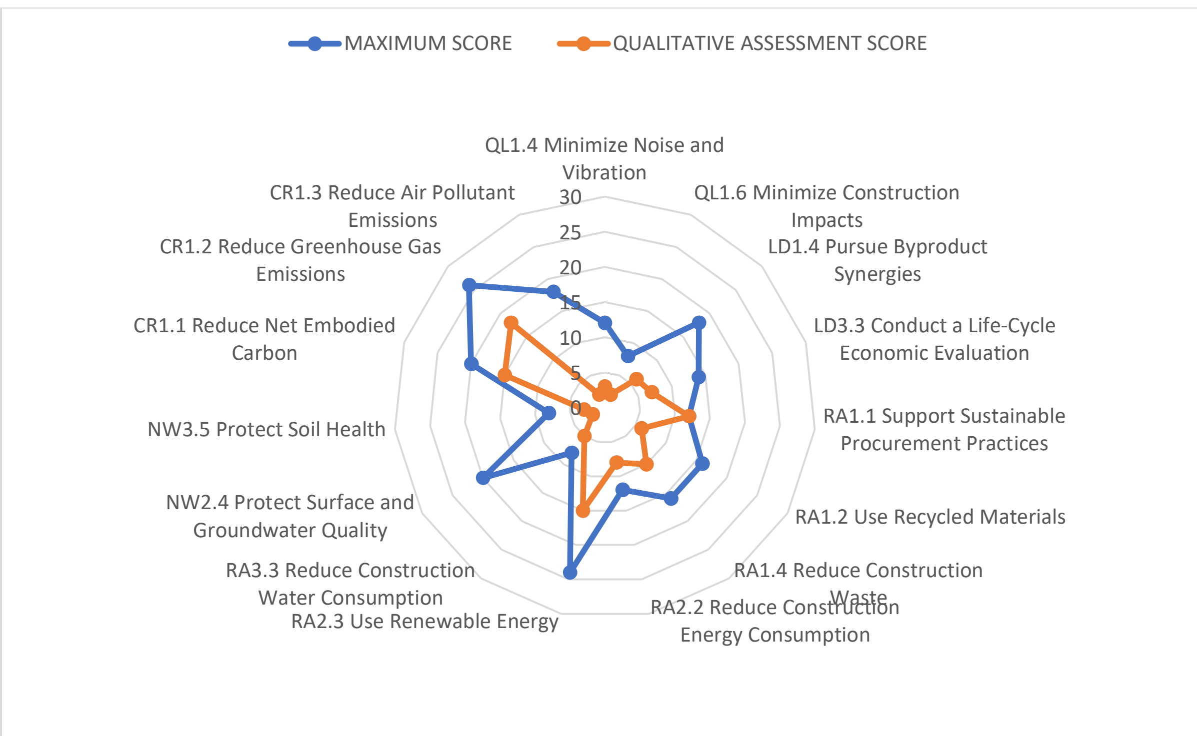


Fig. 7-5, Ground Freezing with Nitrogen technique. Diagram of score contribution vs. each Envision indicator.

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.	**Strategies are implemented** to mitigate noise and/or vibrations during operations. Noise reduction follows a mitigation hierarchy of avoidance/source elimination, minimization, abatement/receiver reduction, and offsetting/compensation."	3	25%	12
QL1.6 Minimize ConstructionI mpacts	QUALITY OF LIFE: WELLBEING	Extent of issues addressed through construction management plans.	The management plan addresses **one (1) type of construction impact**: noise, safety/ wayfinding, access/ mobility, or lighting,	2	25%	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.	The project team demonstrates an active attempt to incorporate **at least one byproduct synergy or reuse** into the project.	6	33%	18
LD3.3 Conduct a Life-Cycle Economic Evaluation	LEADERSHIP: ECONOMY	The comprehensiveness of the economic analyses used to determine the net impacts of the project, and their use in assessing alternatives to inform decision making.	LCCA is used to compare and assess alternatives for **at least one major design component**.	7	50%	14
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 50% 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 15% (by weight, volume, or cost) of recycled materials** including materials with recycled content and/or reused existing structures or materials.	16	100%	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 75% of waste materials are recycled, reused, and/or salvaged**. Diversion may be a combination of waste-reduction measures and sourcing waste to other facilities for recycling or reuse."	10	63%	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 ALLOCATION: 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 Consumption	RESOURCE ALLOCATION: WATER	The number of strategies implemented during construction that reduce potable water consumption.	**At least one (1)** potable water conservation strategy is implemented.	5	63%	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.	**Designs, plans, and programs** instituted to prevent and monitor surface water and groundwater contamination during construction and operations.	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

INDICATOR (CREDIT)	SECTION	METRIC	CRITERIA	SCORE	%	MAX
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 30% reduction in total embodied carbon of materials over the life of the project compared to the baseline. Calculations should be in tons CO2.	15	75%	20
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 50% reduction in total CO2e** over the operational life of the project compared to the baseline. Calculations should be in tons CO2e. (II) The project team maps and calculates the total annual greenhouse gas emissions of the final project design for reporting purposes. This includes direct and indirect greenhouse gas emissions and sequestration associated with project operations. Calculations must be in CO2e.	18	69%	26
CR1.3 Reduce Air Pollutant Emissions	CLIMATE AND RESILIENCE: EMISSIONS	Reduction of air pollutants ompared to baseline.	(I) The project meets all applicable air quality standards and regulations for air pollutants. (II) The project eliminates air pollutant sources in the design, chooses a non-polluting alternative, or achieves at least a 98% net reduction in air pollution emissions compared to the baseline.	9	50%	18
				114	49%	232

Tab. 7-6, Ground Freezing with Nitrogen Freezing technique - The Envision/DNSH framework evaluation for the case study, assigned scores and maximum available scores.

The indicators that scored more than 50% of the maximum admitted total are:

- LD3.3 Conduct a Life-Cycle Economic Evaluation (50%).
- RA1.1 Support Sustainable Procurement Practices (100%).
- RA1.4 Reduce Construction Waste (63%).
- RA2.2 Reduce Construction Energy Consumption (67%).
- RA2.3 Use Renewable Energy (63%).
- RA3.3 Reduce Construction Water Consumption (63%).
- CR1.1 Reduce Net Embodied Carbon (75%).
- CR1.2 Reduce Greenhouse Gas Emissions (69%).

The indicators that scored between 20% and 49% of the maximum admitted total are:

- QL1.4 Minimize Noise and Vibration (25%).
- QL1.6 Minimize Construction Impacts (25%).
- LD1.4 Pursue Byproduct Synergies (33%).
- RA1.2 Use Recycled Materials (38%).
- NW3.5 Protect Soil Health (38%).

The indicators that scored less than 19% of the maximum admitted total are:

- NW2.4 Protect Surface and Groundwater Quality (10%).
- CR1.3 Reduce Air Pollutant Emissions (11%).

Compared to a maximum reachable of 232 points, this ground improvement process scored 114 points (which means an overall value of 49%). When confirmed by the analyses, this could be considered a good scoring (rewardable with a ‘gold’ rating following Envision rating scale).

7.7 Performance comparison at the end of the first phase

The subsequent table provides an overview of the scoring attributed to each approach in relation to each sustainability criteria. The cumulative findings are utilized to determine the overall score inside both the Envision and DNSH frameworks.

In order to assess the ultimate sustainability performance within the Envision/DNSH framework, it is necessary to compare the scores with the maximum attainable and determine the percentage of success.

	Maximum ENVISION Points Available	Minimum ENVISION Points Available	Score Permeation grouting		Score Single fluid Jet Grouting		Score Double fluid Jet Grouting		Score Brine Ground Freezing		Score Nitrogen Ground Freezing	
QL1.4	12	1	1	8%	1	8%	1	8%	3	25%	3	25%
QL1.6	8	1	1	13%	1	13%	1	13%	2	25%	2	25%
LD1.4	18	3	6	33%	6	33%	3	17%	6	33%	6	33%
LD3.3	14	5	7	50%	7	50%	7	50%	7	50%	7	50%
RA1.1	12	3	12	100%	12	100%	12	100%	12	100%	12	100%
RA1.2	16	4	9	56%	9	56%	6	38%	6	38%	6	38%
RA1.4	16	4	7	44%	4	25%	4	25%	10	63%	10	63%
RA2.2	12	1	8	67%	4	33%	1	8%	8	67%	8	67%
RA2.3	24	5	15	63%	15	63%	15	63%	15	63%	15	63%
RA3.3	8	1	3	38%	1	13%	1	13%	5	63%	5	63%
NW2.4	20	2	2	10%	2	10%	2	10%	2	10%	2	10%
NW3.5	8	3	3	38%	3	38%	3	38%	3	38%	3	38%
CR1.1	20	5	15	75%	10	50%	5	25%	15	75%	15	75%
CR1.2	26	3	13	50%	13	50%	8	31%	18	69%	18	69%
CR1.3	18	2	2	11%	2	11%	2	11%	2	11%	2	11%
Envision	232	43	104	45%	90	39%	71	31%	114	49%	114	49%
DNSH	348	68	166	48%	144	41%	114	33%	176	51%	167	48%

Tab. 7-7, First Phase Output: The sustainability performance of the five ground improvement technique under the Envision and the DNSH scoring.

Points are awarded exclusively when the standard criteria is surpassed. Based on the Envision award criteria, which allocate a minimum achievable score of 20% and categorize scores between 20-29% as verified, 30-39% as Silver, 40-49% as Gold, and 50% and above as Platinum, the performance of the techniques examined indicates that they surpass the verified threshold. Notably, brine ground freezing demonstrates a performance that approaches the Platinum level.

These results are plotted in a radar format (see the next figure) in order to emphasize the ‘distribution’ of the scores with respects to the indicators.

Fig. 7-6, First Phase Output: The sustainability performance of the five ground improvement techniques under the Envision and the DNSH scoring. A comparison through the radar diagram view.

The same results are plotted in a multiple bar format (see the next figure) in order to emphasize the relative performance of the techniques with respects to the indicators.

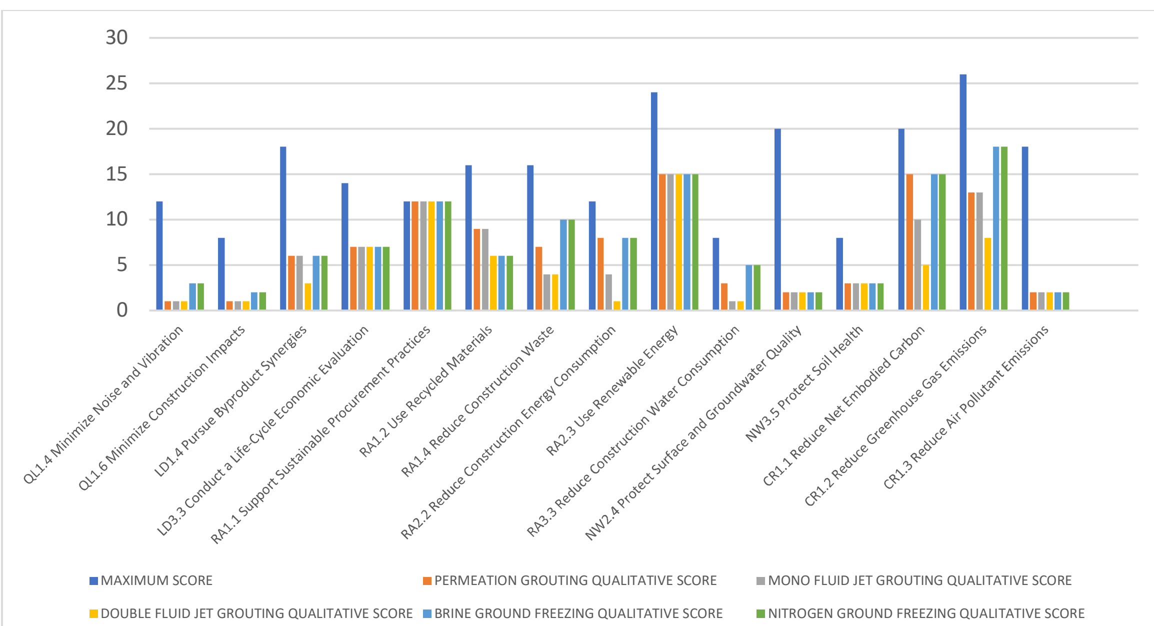


Fig. 7-7, First Phase Output: The sustainability performance of the five ground improvement techniques under the Envision scoring. A comparison for each case and indicator through a bar diagram view.

The diagram demonstrates that, when taking into account the characteristics of the indicators of the Envision/DNSH framework that have been adapted to ground improvement techniques, the area in which to search for more opportunities of good sustainability performances is that which is related to Climate and Resilience (CR1.x, focused on emissions), Resource Allocation (RA1.x, focused on materials and RA2.x focused on energy), and Leadership (LD1.X, focused on collaboration between production sectors). These are the aspects of the process that will receive special focus during the second phase of the approach, which is the life cycle evaluation.

8 The second phase of the sustainability assessment: quantitative evaluation through LCA analyses

8.1 The second phase

This chapter will do a life cycle impact study to evaluate the five ground improvement strategies. The analysis will provide quantitative data, namely the output generated by the numerical models. This data will be utilized to enhance the qualitative assessment that was provided in the preceding chapter.

"LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by: compiling and inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts associated with those inputs and outputs; [and] interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study." [ISO 4040:1997].

The primary objective of LCA documentation is to generate findings pertaining to prospective environmental consequences. In a given context, the term 'potential' pertains to the prospective consequences that may or may not come to fruition based on certain dependent circumstances. From another perspective, the term 'potential' denotes the probability of latent capability inherent in the evaluated commodity or service to influence the environment. The conclusion is predicated on the premise that there exists a defined set of stable and consistent conditions, wherein the likelihood of the real-world outcome aligning with the predicted outcome is significantly high. The statistics pertaining to circumstances, materials, and usage patterns, upon which the Life Cycle Assessment (LCA) conclusion relies, are a crucial component of the stated assumptions within an LCA report. The completeness and accuracy of these sets can significantly influence the results drawn on forecasts of future environmental impact.

When a stakeholder seeks to ascertain the possible environmental effect of a product throughout its life cycle, it is customary to evaluate and record five primary impact categories. Upon thorough evaluation of all pertinent and valid facts, a quantitative measure is allocated to a product or service, signifying its inherent capacity to:

- Create acid rain (acidification).
- Kill streams rivers and oceans (eutrophication).
- Make smog (tropospheric ozone).
- Make the hole in the ozone layer bigger (stratospheric ozone).
- Make di eaeth warner (CO2).
- These five impact categories represent the basic classifications, however they may not encompass all possible aspects related to potential environmental repercussions. Depending on the methodology employed, the primary list has the capacity to be enlarged in order to incorporate the possibility to:Increase the risk to human health.
- Redce the amount f usable land available to all species.
- Decrease the amount of usable water.
- Poison the environment withi toxic chemicals.
- Deplete abuiotic resources including fossil fuels from not renewable deposits.

Abiotic depletion actually spans multiple impact categories since there are many different materials included and varying time horizons of resource renewal.

8.2 Impact frameworks and the choice for the analyses

Methods of a Life Cycle Impact Assessment (LCIA) are used in a Life Cycle Assessment (LCA) to quantify and assess the effects of a given action on the surrounding environment. The life cycle assessment (LCA) begins with the collection of raw data on emissions, waste, and material production. These data must then be converted into a numerical result that is available for interpretation.

Because of the complexity and interconnection of the environment, determining the range of ways in which the environment is impacted and the magnitude of those affects is not a straightforward endeavor. This problem is addressed by the LCIA approaches, which categorize and classify the many kinds of affects that activities have on different parts of the environment, such as the amount of water used, how climate changes, or how poisonous the environment is. The many emissions that result in the same impact are consolidated into a single unit, which then gets mapped onto a single category of impact. As a result, the end result of an LCA will be given in terms of these many classifications.

Depending on the primary purpose of the investigation, several techniques are utilized to quantify various types of effect categories. The adoption of a particular LCIA technique may be a requirement of the standards, as could the requirement to report on particular impact categories.

Because of ots relevance in the construction field, the Environmental Footprint (EF) method was adopted. The Joint Research Centre (JRC), which serves as the research and knowledge service for the European Commission, oversaw the Environmental Footprint program. The project was formally kicked off in 2013, and it has since been split into two phases: the Pilot phase, which lasted from 2013 to 2018, and the Transition phase, which will continue through 2019. The framework presented in the following pages is dated 2021[3].

8.3 The European Environmental Footprint framework

One of the fundamental principles of life cycle thinking is that it offers an exhaustive point of view in identifying impacts and related mitigation opportunities in the phases of choosing materials and approaching the strategy of infrastructure management. Each of the processes or technological strategies that make up the life cycle, whether a material or a construction technology, incorporates the evaluation of energy and resource consumption and the related emission of polluting substances. The extraction and manufacturing processes involved in the production of building materials are responsible for approximately 90% of the environmental pollutants produced during the life cycle of these components. The use of fossil fuels results in emissions of nitrogen oxides (NOx) and carbon dioxide (CO2), which contribute to the adverse environmental effects that occur during transportation and construction. Waste management, especially in construction, often involves the removal of plaster and wood waste, both of which are significant sources of organic acid in landfills. When wood, plastic, and paper are burned, pollutants such as ammonia (NH3), heavy metal ions, and volatile organic compounds (VOCs) are produced. Each of these pollutants can potentially adversely affect human health and the environment. Every construction material and technological device incorporates a part of it to be the arrival point of a technological chain that reaches the finished component from the extraction of primary resources.

[3] https://environment.ec.europa.eu/news/environmental-footprint-methods-2021-12-16_en

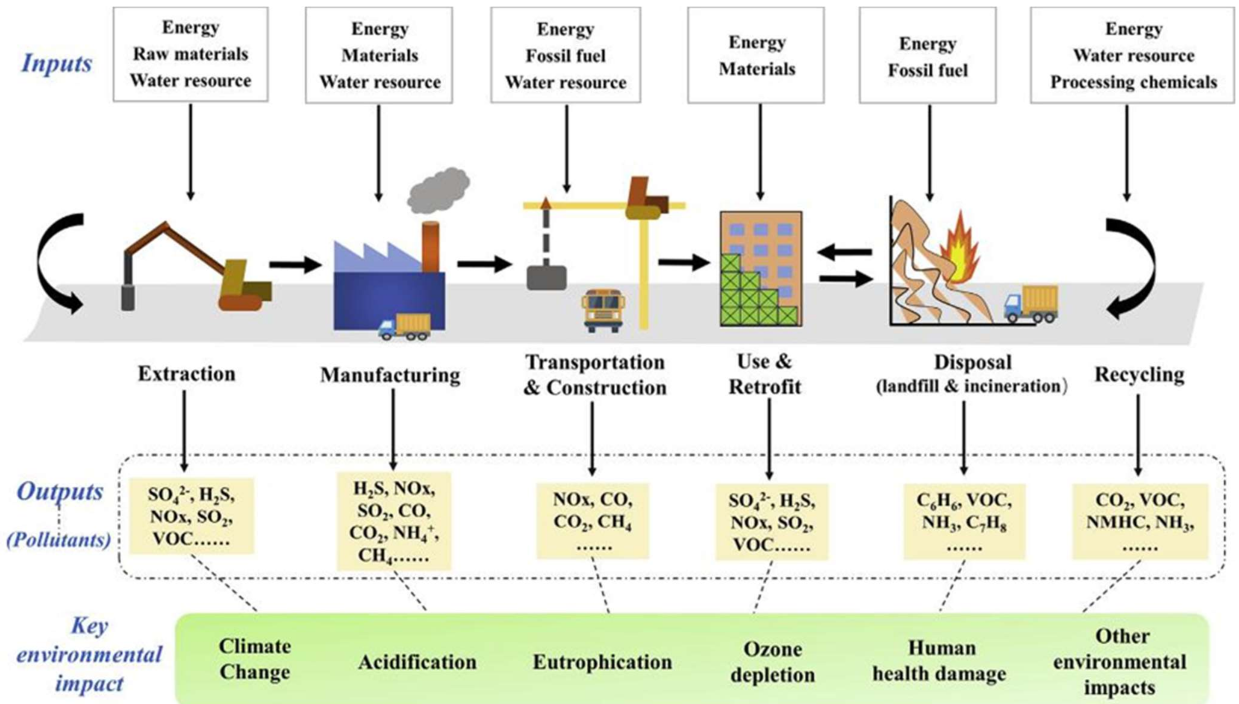


Fig. 8-1, Key Environmental Impacts during the Life Cycle of Building Materials [Huang, 2020]

The European Union has acted as a driving force in the process of implementing the life cycle concept in European product policies over the last two decades [Zamperi et al., 2019]. In particular, Communication COM/2003/302 on Integrated Product Policy has created the primary conditions for the continuous improvement of the environmental performance of all goods during the relevant production, use, and disposal phases. The life cycle approach has become an important lever to guide European policies and investments toward the environmental sustainability objectives the European Union has committed to pursuing (e.g. COM/2019/640 on the European Green Deal).

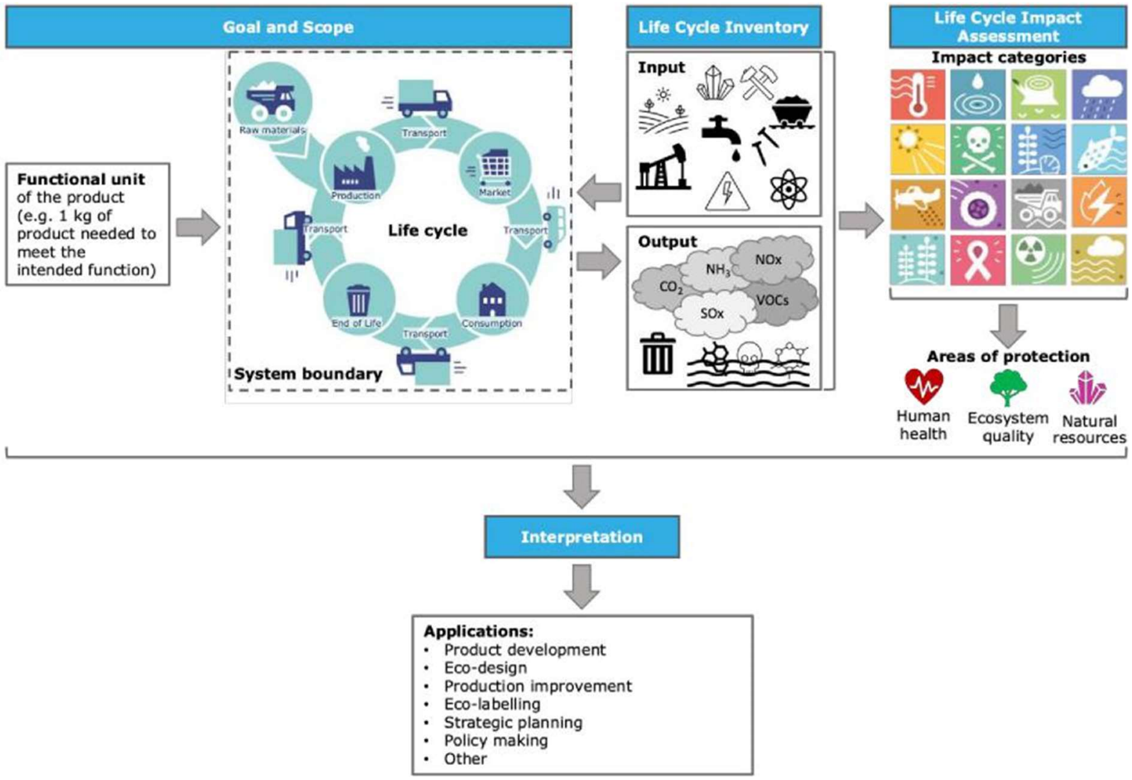


Fig. 8-2, The Environmental Footprint Framework.

Making decisions that have an impact on production processes with a very distant life horizon requires a systemic approach to avoid the feedback that arises from a restriction or conditioning on a part of the system (for example, production), does not result in an amplification of unwanted effects on another party, this is the meaning of the concept of ecological footprint [Damiani, 2022] [Delaurentiis et al., 2019]. In this sense, LCA is the ideal tool precisely because its purpose is to allow an exhaustive investigation of the possible environmental effects that may derive from a specific decision-making procedure. In fact, it combines:

- A life cycle focus: this means that all the stages of a product or service are taken into account, from the extraction of raw materials through processing and production, distribution and use, and the end of life.
- A type of analysis considering a series of distinct environmental effects, effectively a multi-criteria analysis.
- A quantitative methodology: the indicators used are numerical and derived from mathematical models that describe cause-and-effect links and result from various stress factors. (e.g., emissions and use of natural resources).
- A comparative methodology: the life cycle assessment (LCA) method is primarily intended to enable the selection of the optimal course of action between two or more potential outcomes, given the quantitative character of the approach.
- The horizon of the global scale: the analysis can be adapted to systems ranging from the local to the global scale, thus capturing the particularities of these systems concerning the variability of their environments.

The LCA methodology is standardized by regulatory references (ISO 14040 and ISO 14044), which describe the principles, application, phases of an LCA study, requirements, critical review, and reporting. Other ISO standards in the 14040 series complement the general guidelines, such as ISO 14046 for water footprint, and other environmental management standards are linked to ISO 14040-44, such as ISO 14006 (eco-design), ISO

14025 (environmental labeling), ISO 14064 (carbon footprint of organizations), ISO 14067 (carbon footprint of products), ISO 14072 (organizational LCA). In this way, the methodology and approach are uniform and transparent.

1 – Goal and Scope Definition	2 – Life Cycle Inventory Analysis	3 – Life Cycle Impact Assessment
• Reasons and intended applications • Functional unit • System boundary • Impact categories • Allocations • Data requirements • Assumptions and limitations.	Collection of primary and secondary data on elementary and non-elementary flows exchanged through the ecosphere and the technosphere: • input of energy, raw materials, and other physical inputs • output of products, co-products, waste, emissions. Data calculation relating to unit processes, functional unit, and allocations.	Calculation of potential impact associated to the defined impact categories from inventory data. Optional grouping, normalisation, and weighting.

4 – Interpretation
Interpretation of LCIA results, hotspot analysis to find relevant processes and flows, sensitivity analysis of modelling choices, recommendations. The interpretation may involve iteratively reviewing the choices made in the previous stages of the LCA.

Tab. 8-1, Standardized steps of LCA according to ISO 14040-44. Two-way arrows suggest the iterative nature of an LCA. For the technical terms please refer to the section "Nomenclature and Definitions".

The Joint Research Center of the European Commission has significantly contributed to the standardization of LCA by establishing the European International Life Cycle Data System (ILCD, De Wolf et al., 2012). In order to improve the scientific robustness, coherence, reproducibility, and comparability of LCA studies, the objective of the ILCD was to provide in-depth guidelines for the application of LCA to the European context, both from the procedural and scientific.

8.4 The software used for modelling and the implementation of the Environmental Footprint framework

The application to the case study of the five ground improvement techniques is analyzed with a LCA model, as the second step of the proposed three-phased method.

The LCA analyses are performed in this thesis with the software Simapro (rel. 9.5.0.0, 2023) [Pre Consultants, 2018].

The impact framework adopted in the analyses is the Environmental Footprint (EF) method 3.0, originated by an initiative of the European Commission. The method, supported by SimaPro database, includes a number of adaptations, which make the EF method 3.0 implemented compatible with the data libraries provided in SimaPro.

The implementation of the method in Simapro is based on EF method with the following modifications:

- it does not include any substances, which would be new to SimaPro, e.g. regionalized land use flows;
- additional substances have been included as they are extensively used by the background databases and their synonyms are part of the original EF method [Pre Consultants, 2018].

Characterization. The characterization phase of the analysis models the categories in terms of indicators, and, if possible, provides a basis for the aggregation of the inventory input and output within the category.

Characterization is mainly a quantitative step based on scientific analysis of the relevant environmental processes. The characterization assigns the relative contribution of each input and output to the selected impact categories. The potential contribution of each input and output to the environmental impacts is estimated and for some of the environmental impact categories there is consensus about equivalency factors to be used in the estimation of the total impact (e.g. global warming potentials, ozone depletion potentials etc.) whereas equivalence factors for other environmental impacts are not available at consensus level (e.g. biotic resources, land use etc.), depending on the adopted framework.

Normalization. The global normalization set for a reference year 2010 is part of the EF method. These normalization values are updated for the EF 3.0 method in November 2019 and implemented in Simapro.

Many methods allow the impact category indicator results to be compared by a reference (or normal) value. This means that the impact category (in its own unit of measurement) is divided by the reference (with the same unit of measurement). A commonly used reference is the average yearly environmental load in a country or continent, divided by the number of inhabitants. This can be useful to communicate the results to non LCA experts. For our study, we considered the European Community region.

After normalization the impact category indicators are represented by a common unit, which makes it easier to compare them. Normalization can be applied on both characterization and damage assessment results [Benini et al., 2014].

Weighting. The EF 3.0 method only has a single weighting set, which includes toxicity and allow weighting across impact categories. This means the impact (or damage) category indicator results are multiplied by weighting factors and are added to create a total or single score.

How the results will be presented. The results for each case study are presented in terms of characterization, normalization, weighting, and finally single point views. Where needed, there is an additional and specific analysis performed for the relevant subprocesses. As a conclusive paragraph, the five case studies are compared.

8.5 The inventory.

A robust effect evaluation necessitates a comprehensive inventory analysis of meticulously gathered, computed, and assigned data. The calculation of impact category indicator findings can only take place once the final life cycle inventory (LCI) results have been allocated. Therefore, the LCI serves as both a component in establishing the initial objective and scope of a life cycle assessment (LCA) and an internal predecessor to the LCA process. Obtaining fundamental data on the energy, material, and emission fluxes for the numerous unit operations that contribute to a production system is an impractical expectation. Conducting a research only relying on primary data would currently pose significant challenges in terms of time and financial resources. The majority of quantitative information in this context is derived from secondary data, which is maintained by various corporate or governmental entities in cases when source data is unavailable.

The Swiss ecoinvent database[4] provides easily available process data pertaining to several industries, which may be utilized in conducting a Life Cycle Assessment (LCA). The data is commonly subjected to averaging procedures for each specific process and location. Continent- and nation-specific databases, on the other hand,

[4] https://ecoinvent.org/the-ecoinvent-database/

are experiencing steady growth and continuous improvement with each passing year. With the increasing prevalence of data reporting technologies and the corresponding rise in needs, businesses that aggregate data are actively engaged in the evaluation, categorization, and integration of new information sets. This is done with the aim of enhancing the usefulness and pertinence of the services they offer.

The utilization of generic Life Cycle Assessment (LCA) data is particularly suitable during the goal and scope phase. This is because it offers a rapid overview of the areas within a system that may have significant environmental impacts, allowing for the identification of key priorities. By doing so, it helps avoid unnecessary time and effort spent on gathering detailed data for processes that do not contribute significantly to the negative environmental impacts within an LCA model.

8.6 LCA analysis for ground improvement treatment using the permeation grouting technique

8.6.1 Input data

Permeation grouting with TAMs is a widely diffused ground improvement technique. The treatment is performed via 82 PVC sleeved pipes installed in the ground. The injection action ray and the distances between the pipes are such that the theoretical cylindrical volume of soil by a TAM has radius of 0,75m. A distance of 1,20 m is fixed between the pipes, placed along 2 rows. The treated soil wall has a thickness of 2,55 m, for a total volume of 472m3.

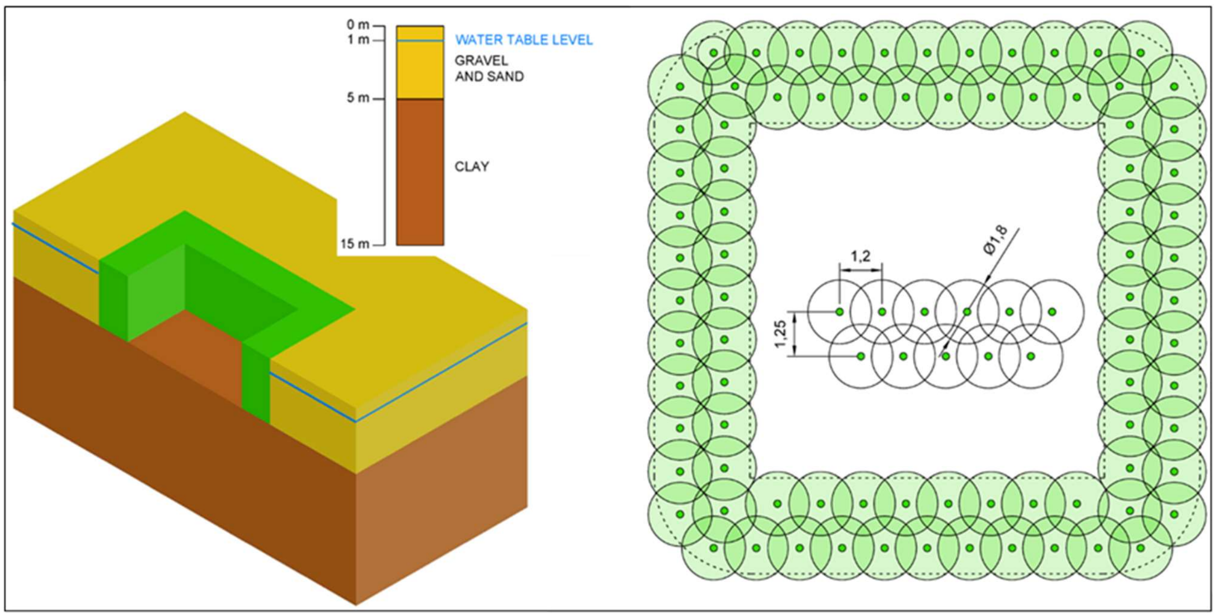


Fig. 8-3, Permeation grouting treatment: geometrical data.

Two main phases can be distinguished. Firstly the PVC pipes installation in the ground, that requires the drilling of the hole, the placement of the pipes and its embedment fixing the pipe surrounding it with a cement-based sheath; after the curing of the latter, it avoided any fluid resurgences during the following injection stage. Then, the injection of the grouted mix is performed By pumping, at low pressure, the cement grout from each valve of the PVC pipe, thus treating the soil and improving its in the surroundings of the TAM. The treatment is performed in order to penetrate the clayey layer for about one meter, in order to create a proper connection between the vertical treated wall and the impervious bottom, guaranteeing the watertightness the excavation. The thickness of 'improved' soil acts as a gravity and waterproofing wall that allows the further excavation to be conducted safely.

In order to focus the case studies on process/technology performance, it has been decided to standardize transports (when requested at the inventory level) with an average distance of 90km. This assumption will be adopted in all the 5 analyzed cases.

The following table gives the main data for the case of permeation grouting.

ITEM	INPUT	VALUE	UNIT	SIMAPRO ECOINVENT REFERENCE
PVC TAM	Product	320	Mass (kg)	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | APOS, U (320kg)
	Process	320	Mass (kg)	Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U (320kg)
	Transport	28800	Mass*Dist (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| APOS, U (320kg * 90km)
Diesel Driller	Consumption	3200	Energy (kWh)	Machine operation diesel, >= 74.57, underground mining (GLO), market for APOS, U (100kW * 32h)
	Product	6500	Mass (kg)	/
	Transport	585000	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (6500kh * 90km)
Electric mixing agitator	Consumption	370	Energy (kWh)	Heat, air-water heat pump 10kW {Europe without Switzerland}| market for floor heating from air-water heat pump | APOS, U (2.2kW * 168hr)
	Product	350	Mass (kg)	/
	Transport	31500	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (350kg * 90km)
Turbomixer (electricity)	Consumption	9	Energy (kWh)	Electricity, medium voltage {IT}| market | APOS, U
	Product	350	Mass (kg)	/
	Transport	31500	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| APOS, U (350kg * 90km)
Electric injection unit mixture+sheath (2 units)	Consumption	1848	Energy (kWh)	Electricity, medium voltage {IT}| market | APOS, U (5.5kW * 2 * 168hr)
	Product	300	Mass (kg)	/
	Transport	300*274 =82200	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport| APOS, U (300kg * 2 * 90km)
Electric turbomixer mixture+sheath	Consumption	768	Energy (kWh)	Electricity, medium voltage {IT}| market | APOS, U
	Product	350	Mass (kg)	/
	Transport	350*274 =95900	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport | APOS, U
Cement	Product	42751	Mass (kg)	Cement, Portland {Europe without Switzerland}| production | APOS, U
	Product	42751	Mass (kg)	Cement, pozzolana and fly ash 11-35% {Europe without Switzerland}| cement production, pozzolana and fly ash 11-35% | APOS, U
	Transport	3847590	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport| APOS, U (42751kg * 90km)
Bentonite	Product	3671	Mass (kg)	Bentonite {RoW}| quarry operation | APOS, U
	Transport	330390	Mass*Dist (kg*km)	Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for transport | APOS, U (3671kg * 90km)
Additive	Product	357	Mass (kg)	Ethylene glycol singleethyl ether {RER}| production | APOS, U
	Transport	32130	Mass*Dist (kg*km)	Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for transport | APOS, U (357kg * 90km)
Water	Water from the tap	105900	Mass (kg)	Tap water {Europe without Switzerland}| market for | APOS, U
	Transport	/	Mass*Dist (kg*km)	/
Mixture waste	Waste	6.36	Volume (m3)	Wastewater from concrete production {RoW}| treatment of, capacity 5E9l/year | APOS, U

Tab. 8-2, LCA analysis input data for permeation grouting.

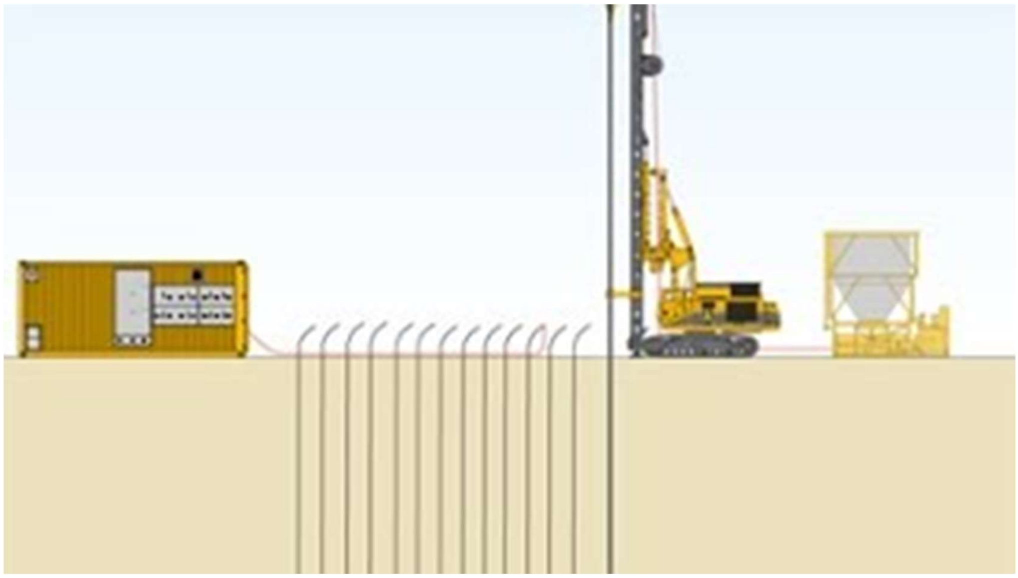


Fig. 8-4, A representation of the permeation grouting technique (Keller website and catalogues).

The study has taken into account a single daily shift of 8 hours for the works. The drilling operation was conducted over a period of four days, utilizing a single diesel drilling rig. The assessment additionally took into account the positioning of the rig for each hole. The execution of sheaths, facilitated by the employment of a modern mixer, has been estimated to take one day.

During the grouting step, it was intended for two electrical injectors to be utilized, with each injector having an average flow rate of 0.3 cubic meters per hour. The treatment involved injecting grout volume equivalent to 28% of the theoretical soil to be treated in two stages. The sequence of these stages is not crucial for the evaluation. The treatment required a total of 31.5 shifts (days) to be completed. The grout was prepared using an electrical turbomixer, then transferred to an electrical mixer agitator, and finally pumped into the injector.

The present study examines a standard ternary grout mixture, characterized by the following weight ratios: cement to water (C/W) ratio of 0.4, binder to cement (B/C) ratio of 0.1, and an additive comprising 1% of the total weight of cement.

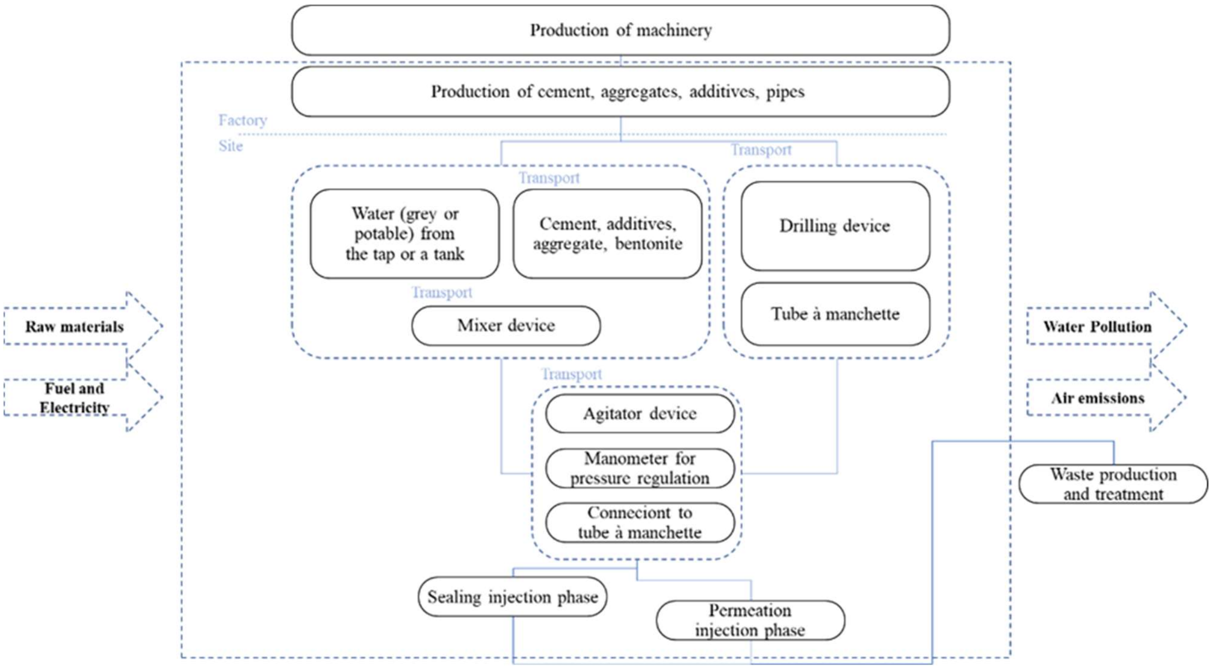


Fig. 8-5, Process scheme for LCA Analysis of the permeation grouting technique.

8.6.2 Permeation grouting LCA analysis

The findings of the life cycle assessment (LCA) analysis for the permeation grouting case study are now presented and discussed in a visual format. The representation of various impacts will be achieved through several perspectives, namely characterized, normalized weighted, and single point, within the selected EF 3.0 impact framework.

The characterisation step of the study involves categorizing indicators and, when feasible, establishing a foundation for aggregating inventory input and output within each category. This is also accomplished in relation to the indication used to signify a comprehensive alteration or burden within that particular category. The outcome of characterisation is the representation of initial loading and resource depletion profile through the combination of category indicators.

The provided visual representation illustrates the correlation between the permeation grouting procedures and the impact categories inside the characterization perspective. The significance of the grouting mix in relation to other processes is evident. However, our analysis reveals that climate change, which is frequently highlighted as a key influence in sustainability reports, is just one of several crucial aspects to consider.

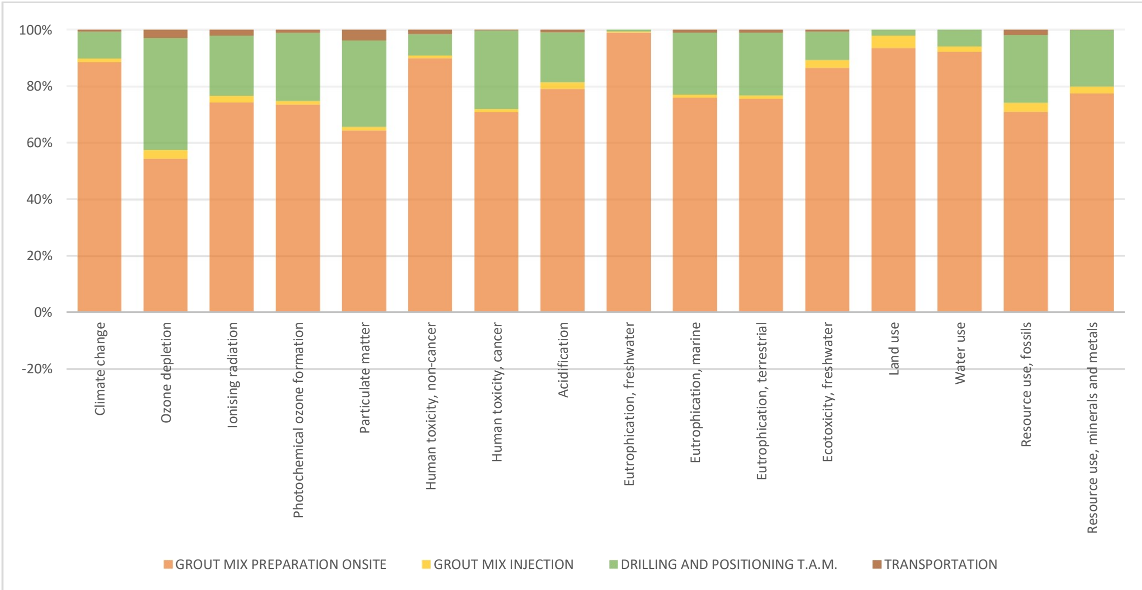


Fig. 8-6, Permeation grouting technique: impacts, characterization view.

This information could have been predicted because of the large mass of the mixture compared to the other shipbuilding objects and, consequently, the high emissions generated by it during production and use in the site. Continuing the analysis will make it possible to understand which impact category is more relevant than the others.

After normalization the impact category indicators all have the same unit, which makes it easier to compare them. Here the relevance of each impact in the framework allows to catch the top offenders of the analysis.

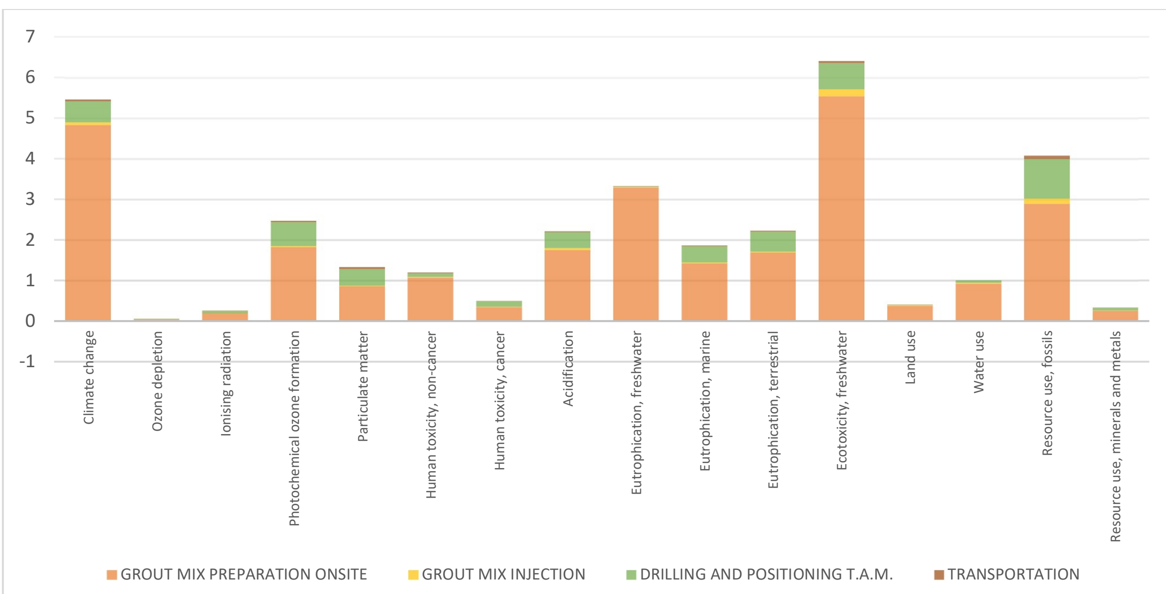


Fig. 8-7, Permeation grouting technique: impacts, normalized view.

The EF 3.0 method has a single weighting set, which includes toxicity and allow weighting across impact categories. This means the impact (or damage) category indicator results are multiplied by weighting factors and are added to create a total or single score.

The application of the weighting coefficients returns the same trend present in the normalization phase.

The following graphs show the final scores for the endpoints expressed as a weighting or as a single score.

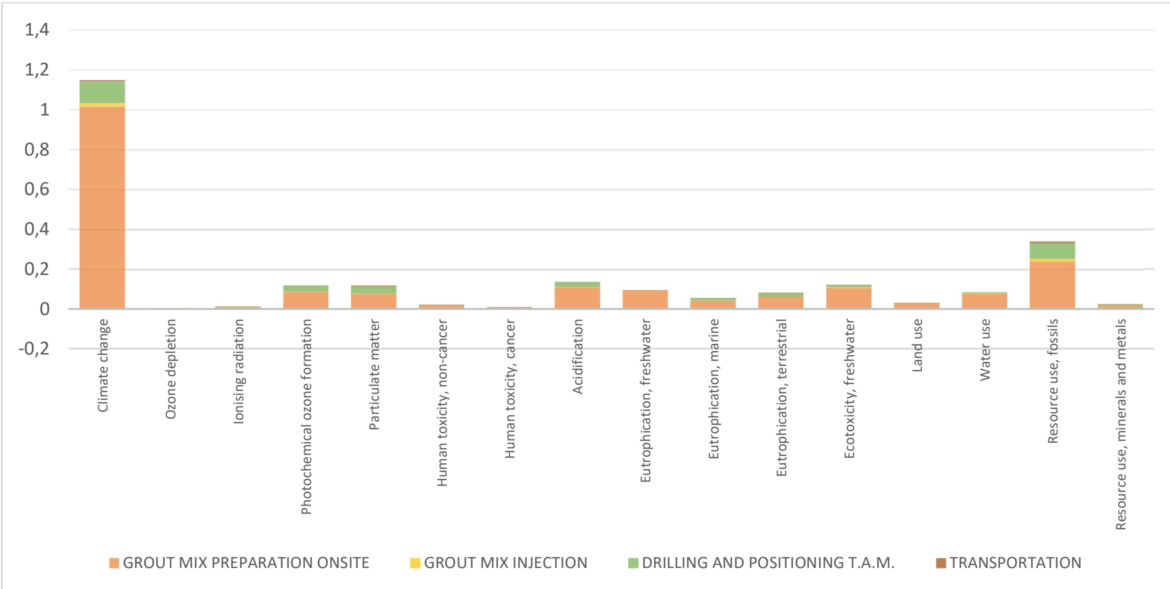


Fig. 8-8, Permeation grouting technique: impacts, weighted view.

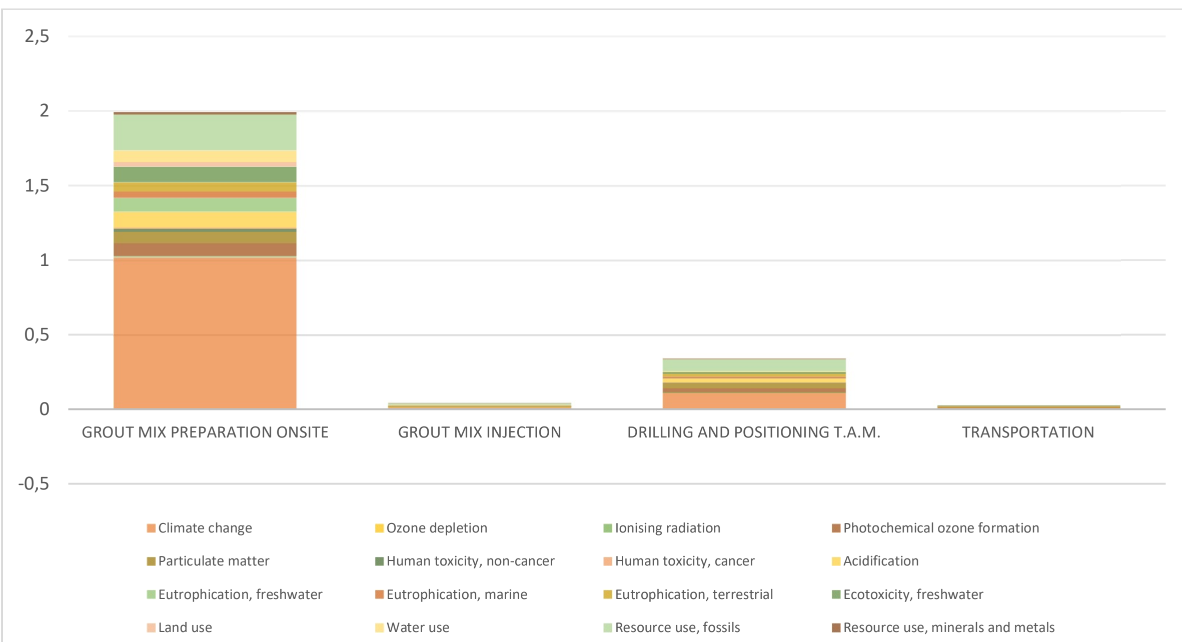


Fig. 8-9, Permeation Grouting technique: impacts, single point view.

The next graph represents the single score impact view for the sub case of the grout mix preparation on site. This view allows to understand the role played by the single components of the grout mix. As expected, cement is in pole position with respect to impact generation.

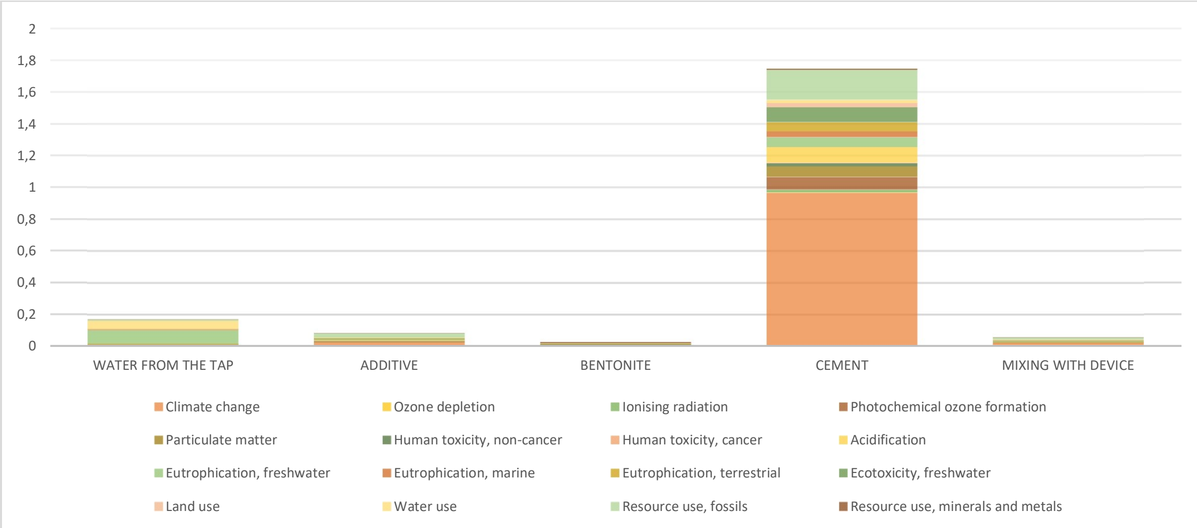


Fig. 8-10, Permeation Grouting technique: grout mix preparation, impacts, single point view.

The following two tables synthetize the impact percentages in the full case and in the grout mix preparation subcase. They are needed in order to make the granular evaluation of the impacts that will be used in the phase of the sustainability framework fine tuning.

Impact category	Unit	Total	GROUTING MIX	INJECTION	DRILLING	TRANSPORTS
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

Tab. 8-3, Permeation Grouting technique: impact percentages, single point.

Impact category	Unit	Total	WATER FROM THE TAP	ADDITIVE	BENTONITE	CEMENT	MIXING WITH DEVICE
Total	%	100,0	8,0	3,9	1,2	84,3	2,6
Climate change	%	49,0	0,4	1,1	0,2	46,5	0,8
Ozone depletion	%	0,1	0,0	0,0	0,0	0,1	0,0
Ionising radiation	%	1,0	0,1	0,0	0,0	0,8	0,0
Photochemical ozone formation	%	4,2	0,0	0,2	0,1	3,8	0,1
Particulate matter	%	3,7	0,0	0,2	0,2	3,3	0,1
Human toxicity, non-cancer	%	0,9	0,0	0,0	0,0	0,9	0,0
Human toxicity, cancer	%	0,4	0,0	0,1	0,0	0,2	0,0
Acidification	%	5,2	0,1	0,2	0,1	4,7	0,2
Eutrophication, freshwater	%	7,6	4,2	0,2	0,0	3,0	0,2
Eutrophication, marine	%	2,1	0,2	0,0	0,0	1,8	0,0
Eutrophication, terrestrial	%	3,0	0,0	0,1	0,0	2,8	0,1
Ecotoxicity, freshwater	%	5,1	0,1	0,2	0,1	4,5	0,2
Land use	%	1,4	0,0	0,0	0,0	1,3	0,1
Water use	%	3,8	2,5	0,2	0,0	1,0	0,2
Resource use, fossils	%	11,6	0,4	1,3	0,1	9,2	0,6
Resource use, minerals and metals	%	0,9	0,0	0,1	0,3	0,4	0,0

Tab. 8-4, Permeation Grouting technique: grout mix preparation, impact percentages, single point.

And finally, the raw data of the characterization step of the analysis, where the quantities of the relevant KPIs of each impact scenario are given.

Impact category	Unit	Total	GROUT MIX PREPARATION ONSITE	GROUT MIX INJECTION	T.A.M. DRILLING AND POSITIONING	MATERIAL AND EQUIPMENT TRANSPORTATION
Climate change	kg CO2 eq	44162,18157	39062,48686	570,03155	4167,30841	362,35474
Ozone depletion	kg CFC11 eq	0,00279	0,00152	0,00009	0,00111	0,00008
Ionising radiation	kBq U-235 eq	2115,31389	1751,90315	71,47018	269,24791	22,69265
Photochemical ozone formation	kg NMVOC eq	100,18710	73,61658	1,25762	24,15130	1,16161
Particulate matter	disease inc.	0,00080	0,00051	0,00001	0,00024	0,00003
Human toxicity, non-cancer	CTUh	0,00027	0,00025	0,00000	0,00002	0,00000
Human toxicity, cancer	CTUh	0,00001	0,00001	0,00000	0,00000	0,00000
Acidification	mol H+ eq	122,69145	96,93313	2,82126	21,72057	1,21648
Eutrophication, freshwater	kg P eq	9,42141	8,99012	0,15533	0,27415	0,00182
Eutrophication, marine	kg N eq	37,41535	28,53300	0,45249	8,04379	0,38606
Eutrophication, terrestrial	mol N eq	393,50655	296,89314	4,76439	87,60686	4,24216
Ecotoxicity, freshwater	CTUe	273202,01072	236308,80508	7365,66684	27327,90529	2199,63351
Land use	Pt	323969,19495	302780,25208	14117,42741	6959,99522	111,52025
Water use	m3 depriv.	11477,57970	10576,18601	214,95153	687,44759	-1,00543
Resource use, fossils	MJ	264587,27601	187619,67118	8515,98291	63394,15336	5057,46855
Resource use, minerals and metals	kg Sb eq	0,02053	0,01589	0,00050	0,00412	0,00002
Climate change - Fossil	kg CO2 eq	44070,27989	38977,67315	566,35006	4163,92277	362,33390
Climate change - Biogenic	kg CO2 eq	60,92449	55,21083	3,14456	2,55176	0,01733
Climate change - Land use and LU change	kg CO2 eq	30,97718	29,60288	0,53692	0,83388	0,00350

Tab. 8-5, Permeation Grouting technique: grout mix preparation, impact percentages, characterization.

From these data two main conclusions can be drawn regarding the permeation grouting technique:

1. the most impacted categories are climate change and resource depletion;

2. the impacting contribution of the mixture compared to the total is equal to 83.3%, while the other relevant contribution is given by drilling with 13.6%.

Keeping this analysis as the baseline, the two points above can drive the sensitivity analysis that follows.

8.6.3 Permeation grouting LCA sensitivity analysis

The requirements/suggestions coming from the qualitative assessment with Envision (i.e. the main leverages to focus on) and the outcomes of the 'baseline' LCA analysis just presented are:

- Energy focus: Improve consumption (a) reducing power production from diesel engines, (b) using electricity coming from providers that use a mix of production that includes renewable sources.
- Transportation focus: Improving the rating of diesel transportation fueled trucks.
- Material focus: for cement, reduce the content in clinker (through pozzolana or fly ash additions).

To the aim of including these sustainability upgrades with respect to the original LCA baseline just described in detail, another sensitivity run of the LCA model has been performed with these upgrades:

- Energy: use of an energy mix 70% fossil and 30% renewable (for instance hydro coming from run off river generation), through the Ecoinvent string: Electricity, high voltage {IT}| electricity production, hydro, run-of-river | APOS, U.
- Cement: use of Pozzolana-based cement instead of Portland-based cement, through the Ecoinvent string: Cement, pozzolana and fly ash 11-35% {Europe without Switzerland}| market for cement, pozzolana and fly ash 11-35% | APOS, U.
- Steel: use of iron coming from scrap, through the Ecoinvent string Iron scrap, unsorted {RoW}| steel production, electric, low-alloyed | APOS, U.
- Transportation: use of trucks Euro6 instead of Euro5, through the Ecoinvent string: Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U.

The analysis is only indicative, because of the 'generic' nature of the data coming from the Ecoinvent database, and more could be done using customized EPDs or material oriented LCAs provided by suppliers, still this sensitivity calculation can give a measure of how much the sustainability performance of the technique could be improved in the light of the suggestions coming from the Envision indicators and the LCA baseline analysis.

The following table gives the results (again in the characterization format) for the sensitivity run.

Impact category	Unit	Total	GROUT MIX PREPARATION ONSITE	GROUT MIX INJECTION	T.A.M. DRILLING AND POSITIONING	MATERIAL AND EQUIPMENT TRANSPORTATION
Climate change	kg CO2 eq	36927,3	32017,1	399,2	4167,3	343,7
Ozone depletion	kg CFC11 eq	0,0	0,0	0,0	0,0	0,0
Ionising radiation	kBq U-235 eq	1824,9	1482,9	50,0	269,2	22,7
Photochemical ozone formation	kg NMVOC eq	86,8	61,3	0,9	24,2	0,5
Particulate matter	disease inc.	0,0	0,0	0,0	0,0	0,0
Human toxicity, non-cancer	CTUh	0,0	0,0	0,0	0,0	0,0
Human toxicity, cancer	CTUh	0,0	0,0	0,0	0,0	0,0
Acidification	mol H+ eq	104,7	80,3	2,0	21,7	0,7
Eutrophication, freshwater	kg P eq	8,7	8,3	0,1	0,3	0,0
Eutrophication, marine	kg N eq	32,5	24,0	0,3	8,0	0,1
Eutrophication, terrestrial	mol N eq	338,0	245,8	3,3	87,6	1,3
Ecotoxicity, freshwater	CTUe	226507,5	191801,8	5178,1	27327,9	2199,8
Land use	Pt	261138,6	244190,9	9876,1	6960,0	111,5
Water use	m3 depriv.	10677,6	9914,5	76,7	687,4	-1,0
Resource use, fossils	MJ	233873,1	159458,6	5962,1	63394,2	5058,3
Resource use, minerals and metals	kg Sb eq	0,0	0,0	0,0	0,0	0,0
Climate change - Fossil	kg CO2 eq	36851,9	31947,7	396,6	4163,9	343,7
Climate change - Biogenic	kg CO2 eq	49,9	45,2	2,2	2,6	0,0
Climate change - Land use and LU change	kg CO2 eq	25,5	24,3	0,4	0,8	0,0

Tab. 8-6, Permeation Grouting technique: sensitivity analysis based on materials, energy and transportation optimizations, impact indicators, characterization.

The subsequent table presents a comparison between the baseline and sensitivity analysis outcomes. The final column on the right provides a summary of the percentage gains and losses relative to the baseline. The detailed commentary on the table will be provided in the third phase of the technique. However, it is evident that there was a significant reduction (-16.38%) in the quantity of CO2e, as well as in all other key performance indicators (KPIs) pertaining to energy and materials usage.

Material/ Consumption	Quantity	Unit
Cement	42751	kg
Energy-Electricity	2995	kWh
Energy-Diesel	3200	kWh
Steel	0	kg
T.A.M.	320	kg
Sludge waste	6.36	m3
Water	105900	kg

	Weighted single score	Total Sensitivity	Total Baseline	Unit	S/B
Climate change	44,89%	36927,3063	44162,18116	kg CO2 eq	-16,38%
Ozone depletion	0,00%	0,00251736	0,002792854	kg CFC11 eq	-9,86%
Ionising radiation	0,00%	1824,891663	2115,313875	kBq U-235 eq	-13,73%
Photochemical ozone formation	4,77%	86,75967776	100,1871036	kg NMVOC eq	-13,40%
Particulate matter	5,03%	0,000714601	0,000796777	disease inc.	-10,31%
Human toxicity, non-cancer	0,00%	0,000229547	0,000273693	CTUh	-16,13%
Human toxicity, cancer	0,00%	7,50983E-06	8,23528E-06	CTUh	-8,81%
Acidification	5,46%	104,6875206	122,6914512	mol H+ eq	-14,67%
Eutrophication, freshwater	7,09%	8,701845279	9,421410615	kg P eq	-7,64%
Eutrophication, marine	0,00%	32,5224058	37,41534811	kg N eq	-13,08%
Eutrophication, terrestrial	0,00%	338,0142282	393,5065501	mol N eq	-14,10%
Ecotoxicity, freshwater	4,76%	226507,5325	273202,0088	CTUe	-17,09%
Land use	0,00%	261138,5881	323969,1919	Pt	-19,39%
Water use	0,00%	10677,62947	11477,57963	m3 depriv.	-6,97%
Resource use, fossils	13,99%	233873,1103	264587,2741	MJ	-11,61%
Resource use, minerals and metals	0,00%	0,018859693	0,020534279	kg Sb eq	-8,16%

Tab. 8-7, Case Study Permeation grouting, sensitivity analysis vs. baseline, total impact indicators, characterization.

8.7 LCA analysis for ground improvement treatment using single fluid jet grouting

8.7.1 Input data

The second methodology employed in the case study is the utilization of the jet grouting technique to enhance and render the soil impermeable in the vicinity of the excavation site. Jet grouting is a widely recognized and extensively studied technology that involves the high-pressure injection of a cement-based grout (comprising water and cement, possibly with the inclusion of additives and/or bentonite) into the ground. This process aims to consolidate soil volumes in situ and enhance its mechanical properties, including resistance and permeability, by thoroughly blending the existing soil with the grout mixture.

Jet grouting is a process that involves the injection of a stabilizing mixture at extremely high pressure (30÷70 MPa, equal to 300÷700 bar) through specialized nozzles. These nozzles, which can be singular or multiple, are positioned at the end of a specialized drilling unit that both spins and is raised. The grout ray, which is introduced through the nozzles, facilitates the fragmentation of the soil. This fragmentation, in conjunction with the rotational movement of the tool, leads to the in-situ mixing of the cement grout and the soil. Consequently, after the curing period of the mixture has passed, a conglomerate soil element known as the jet grouting column is formed. This column exhibits enhanced mechanical and hydraulic properties when compared to the original soil conditions. The process of partially replacing the earth in its original location with cement grout results in the discharge of a spoil material, which consists of a mixture of grout and soil, when it rises to the surface via the drilling hole during the injection process. The mass balancing principle dictates that in the absence of spoil, an elevation of the surface would occur. It is crucial to prevent this phenomena by ensuring proper spoil release during the execution of jet grouting. The quantity of spoil material can range from 100% of the treated ground in cohesive soils to around 50-60% in the case of coarse soils, when drainage mechanisms are at play.

The primary goal of this technology is to achieve a significant level of mechanical soil enhancement and a well-defined geometric configuration, with the dimensions dependent on the energy exerted during the treatment and the properties of the soil. These objectives are typically challenging to accomplish using traditional injection methods. In this work, a grout consisting of water and cement with a water-to-cement ratio (W/C) of about 1 was examined. In contrast, the treatment radius achieved using this particular approach, referred to as single fluid grouting due to the injection of a singular fluid (i.e., cement grout) into the ground, ranges from 0.30 m to 0.5 m, which is less than the radius of action observed in permeation grouting.

In the present study, it has been determined that a total of 202 jet grouting columnar components will be implemented in the examined scenario. These elements will be strategically positioned in three rows encircling the excavation site. The diameter of each column is 1.0m, while the distance between the centers of the columns is 0.75m. The spacing between the rows measures 0.9 meters. The purpose of this geometric pattern is to create a jet grouted soil "wall" that is approximately 2.5 meters thick, covering a treated soil volume of 540 cubic meters.

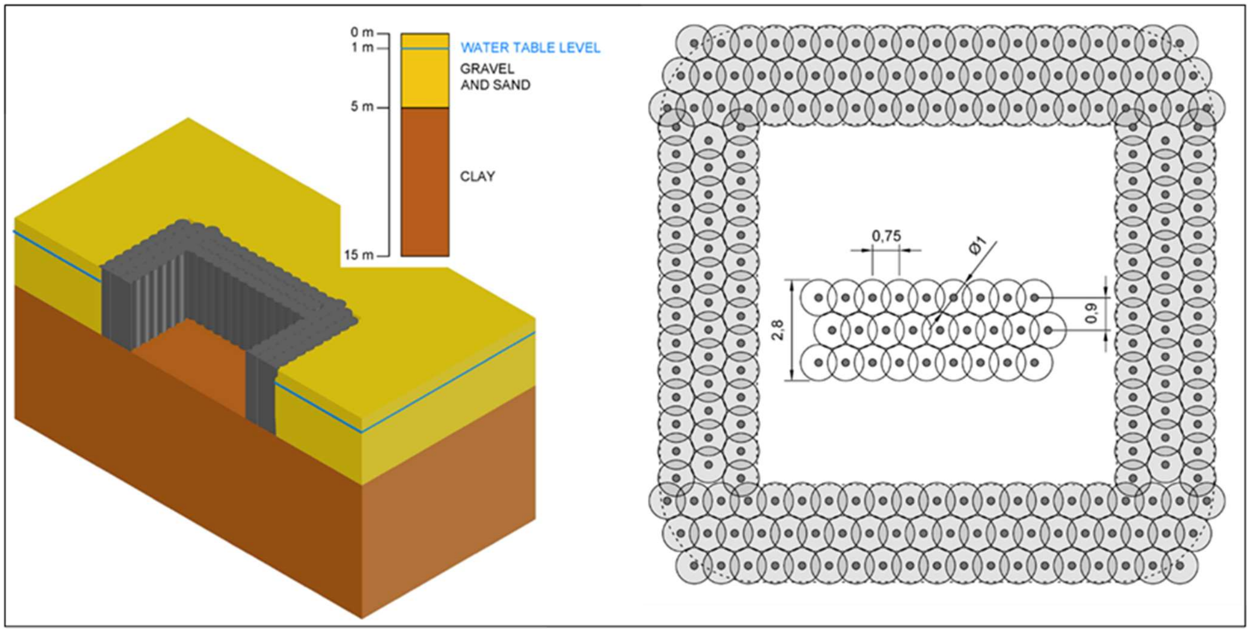


Fig. 8-11, Jet Grouting single fluid technique: geometrical data of the treatment.

In order to focus the case study on process performance, we decided to standardize transports (when requested at the inventory level) with an average distance of 90km.

The following table gives the main input data for the case of single fluid jet grouting treatment. The sizing of this equipment is based on the professional experience of the team in the specific geotechnical construction sector.

ITEM	INPUT	VALUE	UNIT	SIMAPRO ECOINVENT 3 IDENTIFIER
Diesel Driller	Consumption	2516	Duration (hr)	Machine operation diesel, >= 74.57, underground mining (GLO), market for APOS, U (111kW * (34h_drilling+39_injecting))
	Product	6500	Mass (kg)	/
	Transport	585000	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (6500kh * 90km)
Electric Turbomixer	Consumption	2145	Energy (kWh)	Heat, air-water heat pump 10kW {Europe without Switzerland}| market for floor heating from air-water heat pump | APOS, U (55kW * 39hr)
	Product	6600	Mass (kg)	/
	Transport	594000	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (6600kg * 90km)
Electric injection unit mixture	Consumption	14352	Energy (kWh)	Electricity, medium voltage {IT}| market | APOS, U (368kW * 39hr)
	produzio Product	12000	Mass (kg)	/
	Transport	1080000	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport| APOS, U (12000kg * 90km)
Cement	Product	323000	Mass (kg)	Cement, Portland {Europe without Switzerland}| production | APOS, U
	Transport	29070000	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport| APOS, U (323000kg * 90km)
Water	Water from the tap	323000	Mass (kg)	Tap water {Europe without Switzerland}| market for | APOS, U
	Transport	/	Mass*Dist (kg*km)	/
Efflent mixture	Waste	214	Volume (m3)	Wastewater from concrete production {RoW}| treatment of, capacity 5E9l/year | APOS, U

Tab. 8-8, LCA analysis input data for single fluid Jet Grouting.

In contrast to permeation grouting, the process scheme of jet grouting involves the utilization of a drilling rod to facilitate the high pressure injection phase. This drilling rod accommodates injection nozzles that possess the ability to spin and be incrementally elevated in a controlled manner. Moreover, the process of mixing grout primarily involves the combination of two components, namely cement and water, as expected. The gear utilized in this context exhibits higher power consumption compared to the equipment suggested for the permeation grouting scenario, owing to the elevated pressure requirements.

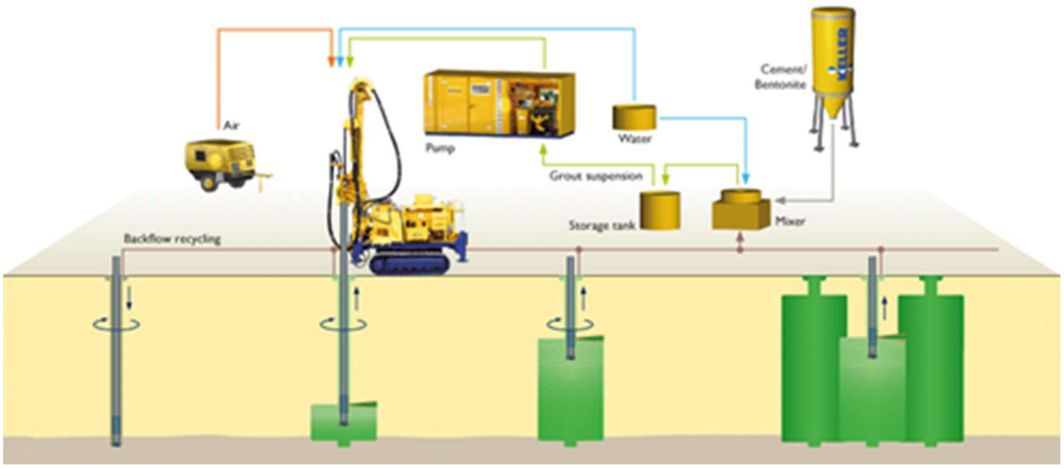


Fig. 8-12, A sitework equipment scheme for single fluid Jet Grouting technique (Keller website and catalogues).

The energy and material flow diagram for this particular approach is presented in the picture seen below. The scheme delineates the parameters of the system under consideration in the model. The primary distinction in the context of permeation grouting pertains to the volume of grouting material required to displace the soil and replace it with the injected mixture, as opposed to permeation grouting which primarily focuses on filling the gaps between soil particles. The surplus of material is counterbalanced by an expedited procedure, resulting in increased efficiency in sitework.

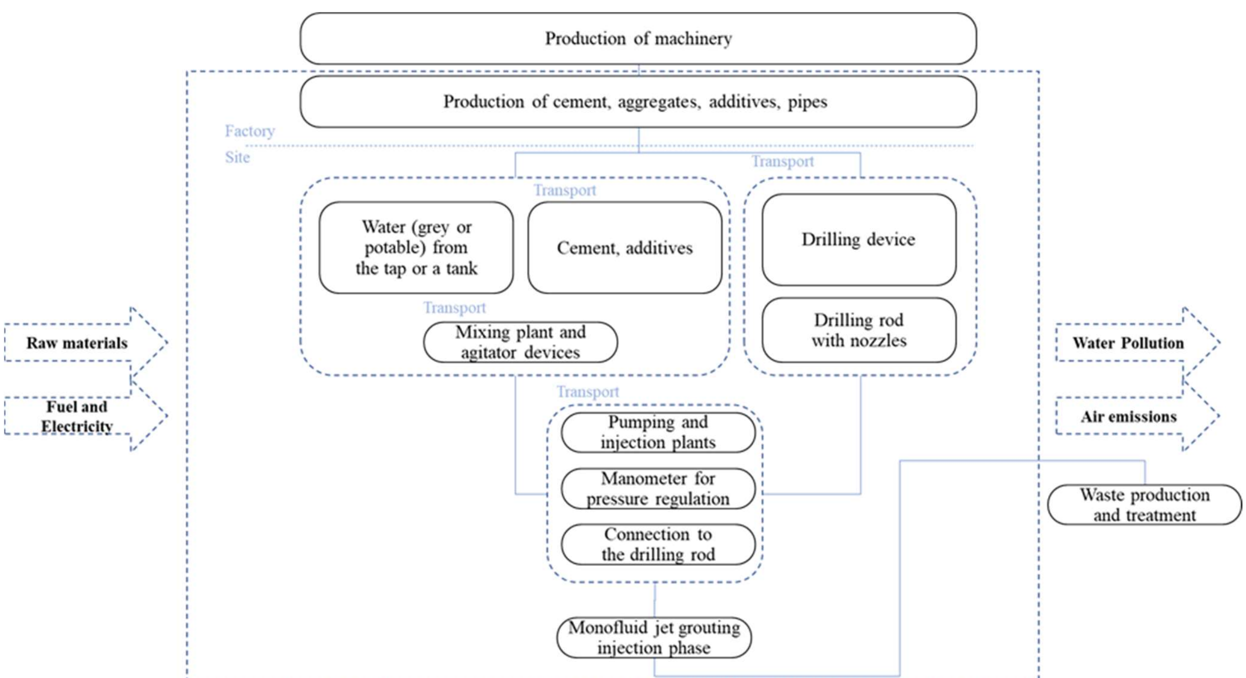


Fig. 8-13, Process scheme for LCA Analysis of the single fluid Jet Grouting technique.

8.7.2 Jet grouting single fluid LCA analysis

The structure of the case study on jet grouting ground improvement using single fluid technology adheres to the recently implemented format employed in the preceding case study. The process consists of four primary stages, including the production of the grout mix, the drilling phase, the injection of the grout mix, and the overall transportation of materials and equipment.

The initial graph pertains to the concept of characterisation. Upon first observation, it is evident that grout mix preparation and injection play a significant role in all categories, particularly when compared to the permeation grouting instance.

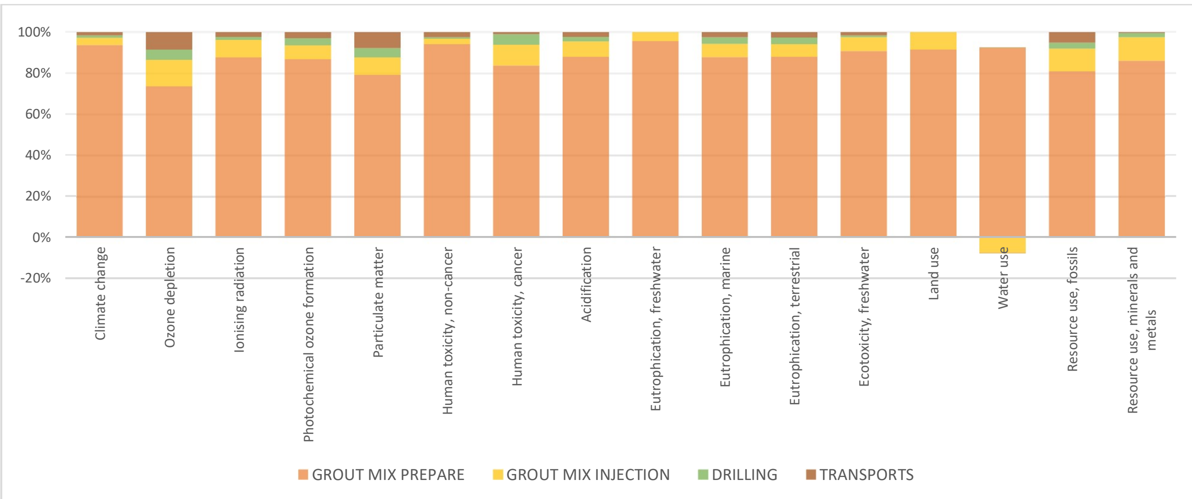


Fig. 8-14, Jet Grouting with single fluid technique: impact, characterization view.

The next image pertains to the normalization of the effects perspective. Once again, the significance of the grouting mix is evident, since it serves as the primary component in all impact schemes. The utilization of the normalization coefficient demonstrates the analogy between the current scenario and the process of permeation grouting, but with a greater emphasis on the mix phase. The primary factor contributing to this phenomenon is the volume of grout mixture utilized in the procedure, since both the disintegration and substitution of soil particles are facilitated by the water/cement mixture.

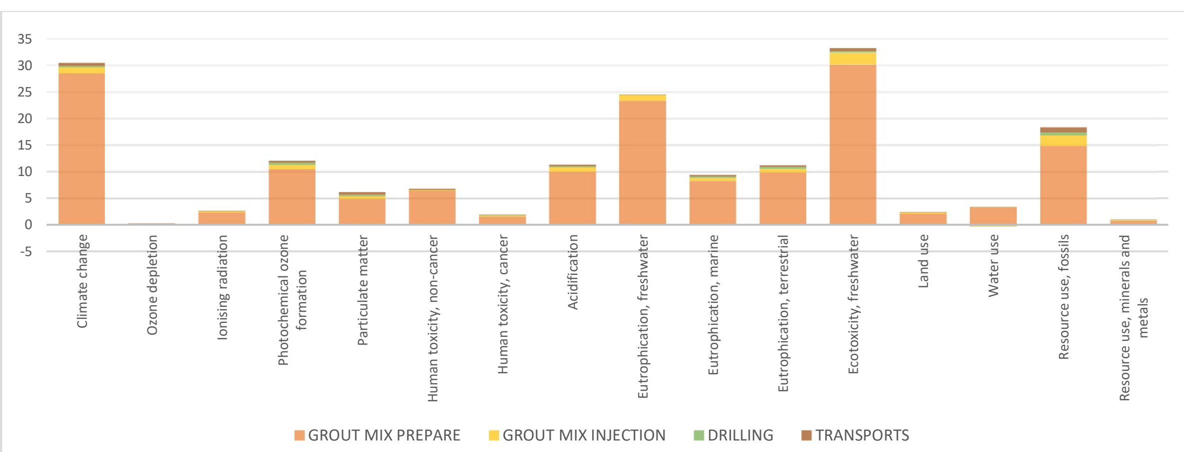


Fig. 8-15, Jet Grouting with single fluid technique: impact, normalization view.

The weighted view puts the impacts in the policy perspective and here the relevant categories are climate change, resource use, water resource depletion and air quality.

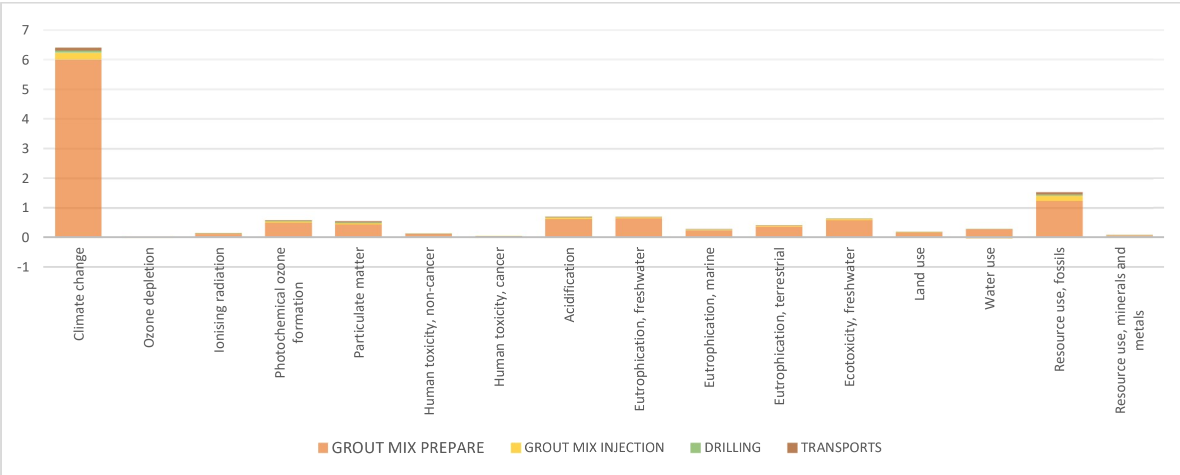


Fig. 8-16, Jet Grouting with single fluid technology: impact, weighted view.

The single point perspective demonstrates the greater effect of this technology compared to its predecessor. The creation of the grout mix is a crucial factor in impact evaluation, with its single point evaluation being more than four times higher than that achieved by the permeation grouting method.

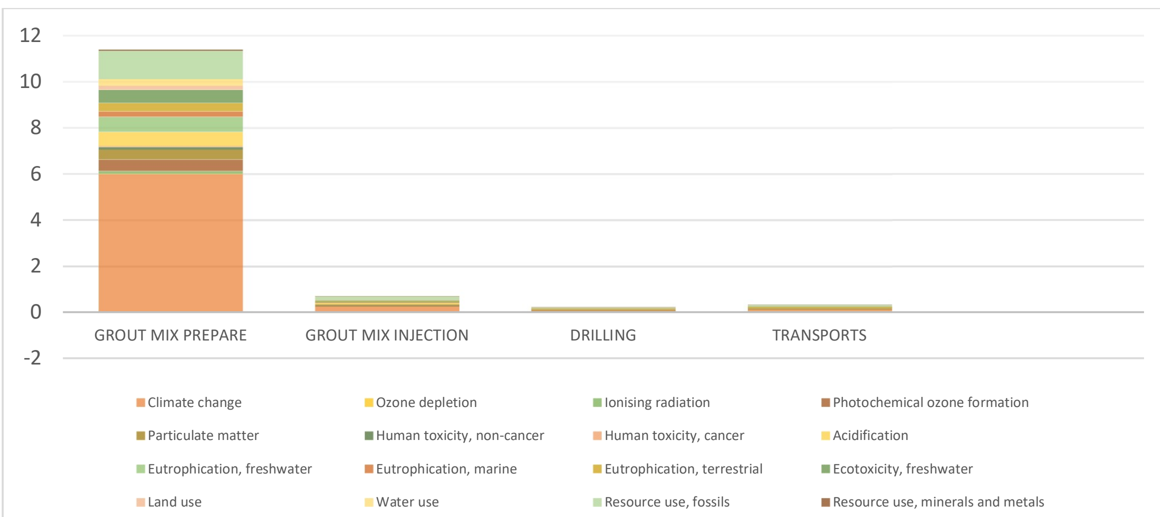


Fig. 8-17, Jet Grouting with single fluid technique: impact, single point/score view.

The table below provides a quantitative representation of the graphical data shown above. The grout mix preparation step accounts for 92.0% of the overall effect, whereas the grout mix injection phase contributes 4.5% to the total impact. This phenomenon can be attributed to the extent of mixture utilized in the treatment process.

Impact category	Unit	Total	GROUT MIX PREPARATION	GROUT MIX INJECTION	DRILLING	TRANSPORTATION
Total	%	100,0	92,0	4,5	1,4	2,1
Climate change	%	51,7	49,0	1,5	0,4	0,8
Ozone depletion	%	0,1	0,1	0,0	0,0	0,0
Ionising radiation	%	1,0	0,9	0,1	0,0	0,0
Photochemical ozone formation	%	4,5	4,0	0,3	0,1	0,1
Particulate matter	%	4,2	3,4	0,3	0,2	0,3
Human toxicity, non-cancer	%	1,0	0,9	0,0	0,0	0,0
Human toxicity, cancer	%	0,3	0,3	0,0	0,0	0,0
Acidification	%	5,6	5,0	0,3	0,1	0,1
Eutrophication, freshwater	%	5,1	4,9	0,2	0,0	0,0
Eutrophication, marine	%	2,2	2,0	0,1	0,1	0,0
Eutrophication, terrestrial	%	3,3	3,0	0,2	0,1	0,1
Ecotoxicity, freshwater	%	5,2	4,8	0,3	0,0	0,1
Land use	%	1,5	1,4	0,1	0,0	0,0
Water use	%	1,9	2,1	-0,2	0,0	0,0
Resource use, fossils	%	11,8	9,8	1,1	0,3	0,5
Resource use, minerals and metals	%	0,5	0,5	0,1	0,0	0,0

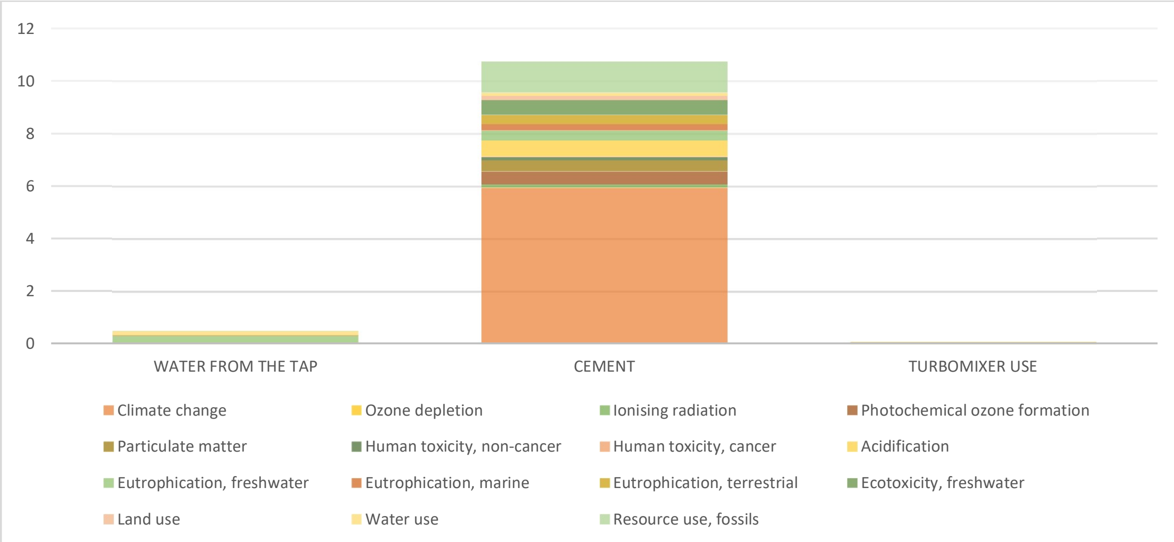
Tab. 8-9, Jet grouting with single fluid technique: impact percentages, single point view.

The characterisation findings are examined and given in the following table as a quantitative output for each impact's single Key Performance Indicator (KPI).

Impact category	Unit	Total	GROUT MIX ON SITE	GROUT MIX INJECTION	DRILLING	MATERIAL AND EQUIPMENT TRANSPORTATION
Climate change	kg CO2 eq	297937,36190	282049,05247	8883,53844	2577,77979	4426,99120
Ozone depletion	kg CFC11 eq	0,01348	0,01034	0,00153	0,00058	0,00103
Ionising radiation	kBq U-235 eq	13043,89159	11656,01668	949,13030	157,35355	281,39106
Photochemical ozone formation	kg NMVOC eq	578,32742	513,28082	33,20640	17,07448	14,76572
Particulate matter	disease inc.	0,00419	0,00343	0,00031	0,00017	0,00029
Human toxicity, non-cancer	CTUh	0,00187	0,00177	0,00004	0,00001	0,00004
Human toxicity, cancer	CTUh	0,00004	0,00003	0,00000	0,00000	0,00000
Acidification	mol H+ eq	745,56101	669,35194	46,81155	14,06494	15,33257
Eutrophication, freshwater	kg P eq	43,87501	42,08826	1,74656	0,01766	0,02253
Eutrophication, marine	kg N eq	215,75604	193,21662	11,90175	5,71770	4,91996
Eutrophication, terrestrial	mol N eq	2349,61080	2108,46807	124,16053	62,86361	54,11858
Ecotoxicity, freshwater	CTUe	1734046,34881	1601595,13413	95244,28638	11997,76319	25209,16511
Land use	Pt	2269326,77709	2108360,84166	158112,54792	1470,52547	1382,86204
Water use	m3 depriv.	38826,54249	41983,03649	-3151,32446	7,29788	-12,46743
Resource use, fossils	MJ	1379881,30564	1152103,68691	129600,31070	35464,20034	62713,10770
Resource use, minerals and metals	kg Sb eq	0,06825	0,06006	0,00670	0,00118	0,00030
Climate change - Fossil	kg CO2 eq	297313,36970	281466,59932	8842,46613	2577,57146	4426,73280
Climate change - Biogenic	kg CO2 eq	404,75280	369,30702	35,06431	0,16651	0,21495
Climate change - Land use and LU change	kg CO2 eq	219,23940	213,14613	6,00800	0,04182	0,04345

Tab. 8-10, Jet grouting with single fluid technique: impact percentages, characterization.

To further delve into the process of grout mix production, a singular point plot is provided to illustrate a specific step of the mix preparation. Once again, cement stands up as the primary factor responsible for significant impacts. According to the single point evaluation, the contribution of cement to the effect score is 10 times more than that of the other components.



Tab. 8-11, Jet grouting with single fluid technique: grout mix preparation focus, impact, single score view.

More in detail, the next table gives the single quantitative contributions, with more than 95% of the impacts performed by cement.

Impact category	Unit	Total	WATER ON SITE	CEMENT ON SITE	TURBOMIXING
Total	%	100,0	3,7	95,8	0,6
Climate change	%	53,2	0,2	52,9	0,2
Ozone depletion	%	0,1	0,0	0,1	0,0
Ionising radiation	%	1,0	0,0	1,0	0,0
Photochemical ozone formation	%	4,4	0,0	4,4	0,0
Particulate matter	%	3,7	0,0	3,7	0,0
Human toxicity, non-cancer	%	1,0	0,0	1,0	0,0
Human toxicity, cancer	%	0,3	0,0	0,3	0,0
Acidification	%	5,4	0,0	5,3	0,0
Eutrophication, freshwater	%	5,3	1,9	3,4	0,0
Eutrophication, marine	%	2,1	0,1	2,0	0,0
Eutrophication, terrestrial	%	3,2	0,0	3,2	0,0
Ecotoxicity, freshwater	%	5,2	0,1	5,1	0,0
Land use	%	1,5	0,0	1,5	0,0
Water use	%	2,3	1,1	1,1	0,0
Resource use, fossils	%	10,7	0,2	10,4	0,1
Resource use, minerals and metals	%	0,5	0,0	0,5	0,0

Tab. 8-12, Jet grouting with single fluid technique: impact percentages, single point view, mix preparation phase.

8.7.3 Jet grouting single fluid LCA sensitivity analysis

The recommendations derived from the qualitative evaluation conducted with Envision (i.e., the primary areas of emphasis) are as follows:

- Energy: Enhance efficiency in energy usage by (a) minimizing reliance on diesel engines for power generation and (b) utilizing electricity sourced from suppliers employing a diverse mix of renewable energy production methods.
- Transportation: Enhancing the performance of trucks powered by diesel fuel.

One potential approach to reducing the content of clinker in cement is by including alternative binders such as pozzolana or fly ash.

In order to incorporate the aforementioned sustainability enhancements in relation to the comprehensive description of the original Life Cycle Assessment (LCA) baseline, an additional iteration of the LCA model has been conducted, including these improvements.

- The proposed energy solution involves utilizing a combination of fossil fuels and renewable sources, with a distribution of 70% and 30% respectively. An example of a renewable source that may be incorporated is hydroelectric power generated from run-off river systems. This energy mix will be implemented using the Ecoinvent string: Electricity, high voltage {IT}| electricity production, hydro, run-of-river | APOS, U.
- It is recommended to utilize Pozzolana-based cement as an alternative to Portland-based cement, as shown by the Ecoinvent string: Cement, pozzolana and fly ash 11-35% {Europe without Switzerland}| market for cement, pozzolana and fly ash 11-35% | APOS, U.
- Steel: use iron coming from scrap, through the Ecoinvent string Iron scrap, unsorted {RoW}| steel production, electric, low-alloyed | APOS, U.
- Transportation: use trucks Euro6 instead of Euro5, through the Ecoinvent string: Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U.

The analysis provided is merely suggestive due to the inherent generality of the data sourced from the Ecoinvent database. However, further improvements can be made by utilizing customized Environmental Product Declarations (EPDs) or conducting material-oriented Life Cycle Assessments (LCAs) provided by suppliers. Nevertheless, the sensitivity calculation presented offers an indication of the potential enhancements that can be achieved in the sustainability performance of the technique, taking into account the recommendations derived from the Envision indicators. The next table gives the output of the sensitivity runs.

Impact category	Unit	Total	GROUT MIX ON SITE	GROUT MIX INJECTION	DRILLING	MATERIAL AND EQUIPMENT TRANSPORTATION
Climate change	kg CO2 eq	243865,88475	230043,85068	6988,08500	2577,77979	4256,16929
Ozone depletion	kg CFC11 eq	0,01146	0,00865	0,00125	0,00058	0,00099
Ionising radiation	kBq U-235 eq	10917,13495	9777,38980	711,35360	157,35355	271,03799
Photochemical ozone formation	kg NMVOC eq	474,33955	422,71863	29,02380	17,07448	5,52263
Particulate matter	disease inc.	0,00356	0,00287	0,00028	0,00017	0,00025
Human toxicity, non-cancer	CTUh	0,00153	0,00145	0,00003	0,00001	0,00004
Human toxicity, cancer	CTUh	0,00003	0,00003	0,00000	0,00000	0,00000
Acidification	mol H+ eq	609,58859	549,67268	37,42562	14,06494	8,42534
Eutrophication, freshwater	kg P eq	38,60662	37,33683	1,23044	0,01766	0,02170
Eutrophication, marine	kg N eq	177,78931	160,21344	10,45464	5,71770	1,40353
Eutrophication, terrestrial	mol N eq	1919,40385	1732,62204	108,31313	62,86361	15,60507
Ecotoxicity, freshwater	CTUe	1388365,94139	1281018,66241	70973,72194	11997,76310	24375,79393
Land use	Pt	1809977,70088	1696118,12338	111057,06889	1470,52546	1331,98315
Water use	m3 depriv.	33285,37621	37975,12512	-4685,03807	7,29788	-12,00872
Resource use, fossils	MJ	1154790,31223	957654,03542	101266,33782	35464,20007	60405,73891
Resource use, minerals and metals	kg Sb eq	0,05613	0,04961	0,00505	0,00118	0,00029
Climate change - Fossil	kg CO2 eq	243362,43334	229569,67868	6959,26281	2577,57146	4255,92039
Climate change - Biogenic	kg CO2 eq	325,12613	300,15275	24,59982	0,16651	0,20704
Climate change - Land use and LU change	kg CO2 eq	178,32529	174,01925	4,22236	0,04182	0,04185

Tab. 8-13, Jet Grouting with single fluid technique: sensitivity analysis based on materials, energy and transportation optimizations, impact indicators, characterization.

The subsequent table presents a comparative analysis between the baseline and sensitivity runs. The utilization of a more sustainable composition for concrete, coupled with a combination of fossil and renewable energy sources, results in a noteworthy decrease of around 18.15% in carbon dioxide equivalent emissions (CO2e).

Material/ Consumption	Quantity	Unit
Cement	323000	kg
Energy-Electricity	16497	kWh
Energy-Diesel	2516	kWh
Steel	0	kg
T.A.M.	0	kg
Sludge waste	214	m3
Water	323000	kg

	Weighted single score	Total Sensitivity	Total Baseline	Unit	S/B
Climate change	0,00%	243865,88401	297937,36176	kg CO2 eq	-18,15%
Ozone depletion	0,00%	0,01146	0,01348	kg CFC11 eq	-15,02%
Ionising radiation	4,52%	10917,13489	13043,89158	kBq U-235 eq	-16,30%
Photochemical ozone formation	4,34%	474,33955	578,32742	kg NMVOC eq	-17,98%
Particulate matter	0,00%	0,00356	0,00419	disease inc.	-15,05%
Human toxicity, non-cancer	0,00%	0,00153	0,00187	CTUh	-17,81%
Human toxicity, cancer	5,50%	0,00003	0,00004	CTUh	-15,03%
Acidification	5,44%	609,58859	745,56100	mol H+ eq	-18,24%
Eutrophication, freshwater	0,00%	38,60662	43,87501	kg P eq	-12,01%
Eutrophication, marine	0,00%	177,78931	215,75604	kg N eq	-17,60%
Eutrophication, terrestrial	5,05%	1919,40385	2349,61079	mol N eq	-18,31%
Ecotoxicity, freshwater	0,00%	1388365,93687	1734046,34667	CTUe	-19,93%
Land use	0,00%	1809977,69765	2269326,77323	Pt	-20,24%
Water use	11,96%	33285,37621	38826,54247	m3 depriv.	-14,27%
Resource use, fossils	0,00%	1154790,30521	1379881,30282	MJ	-16,31%
Resource use, minerals and metals	0,00%	0,05613	0,06825	kg Sb eq	-17,76%

Tab. 8-14, Case Study Jet Grouting Single fluid, sensitivity analysis vs. baseline, total impact indicators, characterization.

8.8 LCA analysis input for ground improvement treatment using double fluid jet grouting

8.8.1 Input data

The third case study examines the application of an alternative jet grouting approach aimed at enhancing the mechanical properties and water resistance of the soil next to the excavation site. Specifically, it focuses on the implementation of the double-fluid jet grouting treatment. In addition, compressed air is utilized as the mixing fluid in conjunction with the cement grout. Compressed air exhibits significant penetrating and disintegrating capabilities when applied to the ground, hence facilitating the expansion of jet grouting columns to dimensions exceeding 3 meters. The drilling rig is equipped with a specifically designated conduit for the air, which is introduced into the system at a flow rate of 10 cubic meters per minute and a pressure of 10 bar. The utilization of specialized concentric nozzles enables the simultaneous directional control of many fluids. The mechanical and hydraulic characteristics of the treated soil exhibit similarities to those of soil treated with single-fluid jet grouting. This technique is employed in situations when there is a need for large-scale manufacturing and extensive treatment, such as the installation of plugs, foundation structures, and impermeable curtains.

The ground treatment is implemented by conducting 84 jet grouting columns with a diameter of 2.50 meters, arranged in two rows on either side of the excavation area. The spacing between the columns is measured at 1.20 meters, while the space between the rows is recorded as 1.25 meters. The column pattern is strategically engineered to generate a soil "wall" with enhanced properties, measuring around 2.5 meters in thickness. This is achieved by the process of jet grouting, which involves the injection of a high-pressure grout into the soil, resulting in the formation of columns. The total volume of soil treated using this method amounts to 540 cubic meters.

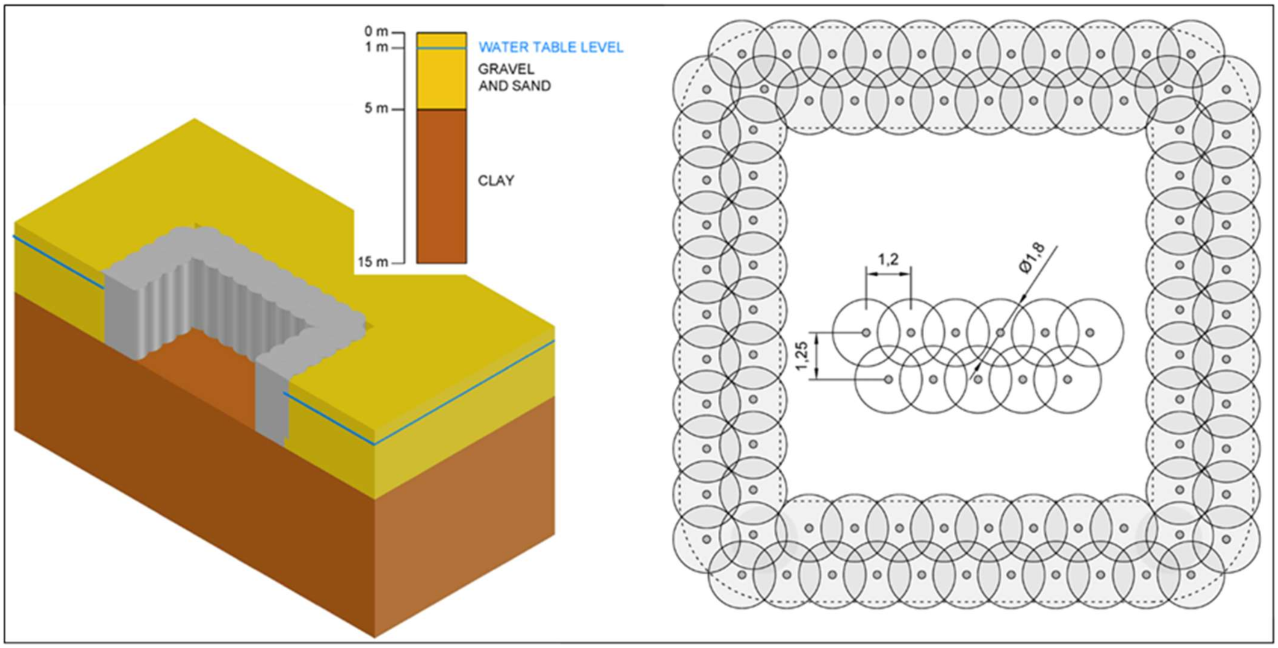


Fig. 8-18, Jet grouting with double fluid technique: geometrical data.

As for the other cases, in order to focus the pilot case on process performance, we decided to standardize transports (when requested at the inventory level) with an average distance of 90km.

The following table gives the main data for our case of double fluid jet grouting treatment.

ITEM	INPUT	VALUE	UNIT	SIMAPRO ECOINVENT REFERENCE
Diesel Driller	Consumption	1050	Duration (hr)	Machine operation diesel, >= 74.57, underground mining (GLO), market for APOS, U (111kW * (14h_drilling+26_injecting))
	Product	9000	Mass (kg)	/
	Transport	810000	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (6500kh * 90km)
Electric Turbomixer	Consumption	1430	Energy (kWh)	Heat, air-water heat pump 10kW {Europe without Switzerland}| market for floor heating from air-water heat pump | APOS, U (55kW * 26hr)
	Product	6600	Mass (kg)	/
	Transport	594000	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (6600kg * 90km)
Electric injection unit mixture	Consumption	9568	Energy (kWh)	Electricity, medium voltage {IT}| market | APOS, U (368kW * 26hr)
	produzio Product	12000	Mass (kg)	/
	Transport	1080000	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport| APOS, U (12000kg * 90km)
Cement	Product	425000	Mass (kg)	Cement, Portland {Europe without Switzerland}| production | APOS, U
	Transport	38250000	Mass*Dist (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport| APOS, U (425000kg * 90km)
Water	Water from the tap	425000	Mass (kg)	Tap water {Europe without Switzerland}| market for | APOS, U
	Transport	/	Mass*Dist (kg*km)	/
Efflent mixture	Waste	283	Volume (m3)	Wastewater from concrete production {RoW}| treatment of, capacity 5E9l/year | APOS, U

Tab. 8-15, Jet grouting with double fluid technique: LCA analysis input data.

The double fluid method utilizes high pressure in conjunction with a mixture of air and grout to achieve larger column diameters, resulting in a significant decrease in drilling time. In our particular scenario, it may be inferred that achieving stability in the excavation can be accomplished by employing two rings of columns, as opposed to the previously assumed requirement of three. There are no other significant alterations seen in the structure of the preceding process scheme.

In the context of treatment execution, it is assumed that the average drilling production rate is 30 meters per hour. This rate includes the positioning of the drilling unit on each column axis. As a result, the cumulative duration of the drilling phase for the columns amounted to 14 hours.

During the jet grouting phase, the selection of operational parameters such as pressure, cement quantity, and uplift velocity was determined based on the natural soil composition and density. To achieve the desired results, a pressure of 50 MPa was applied, accompanied with the injection of about 425 tons of 32.5 Portland cement. The uplift velocity during this process was maintained at 13.1m/h. The completion of all the columns necessitated around 26 hours. In addition to this, consideration was given to the operation of an electric mixer for the preparation of the grout mixture, a high-pressure pump for the injection process, an air compressor, and, of course, the drilling unit.

A spoil output rate of 50% was assumed for the amount of soil that was treated.

8.8.2 Jet grouting double fluid LCA analysis

The double fluid jet grouting method offers notable advantages in terms of enhanced effectiveness and expedited processes. However, a careful examination of the quantities table reveals that this technique necessitates a greater consumption of resources and energy. Anticipated is the development of a technologically advanced system that will yield more efficacy, akin to the level of effectiveness observed in the context of single fluid jet grouting. The narrative of the characterization perspective compels us to make similar observations as those made for the single fluid technology, namely regarding the significant influence on the grout mix-related stages.

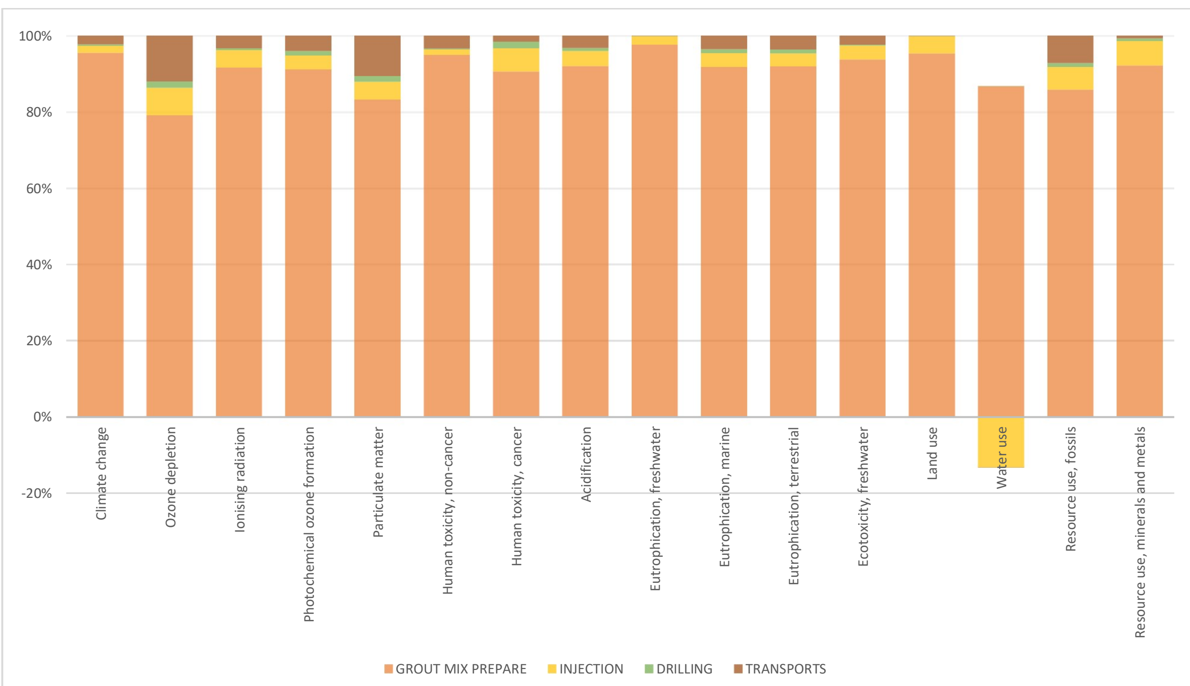


Fig. 8-19, Jet grouting with double fluid technique: impact, characterization view.

The normalization and weighting analyses reveal that climate change, resource consumption, air quality, and water resource depletion are identified as the primary areas of effect.

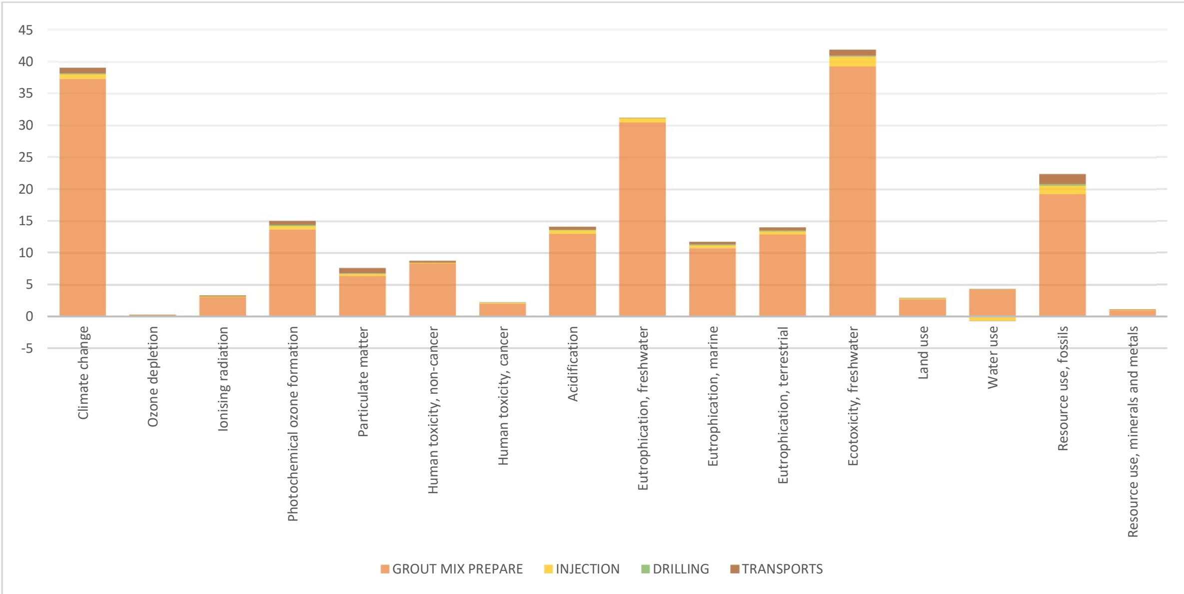


Fig. 8-20, Jet grouting with double fluid technique: impact, normalized view.

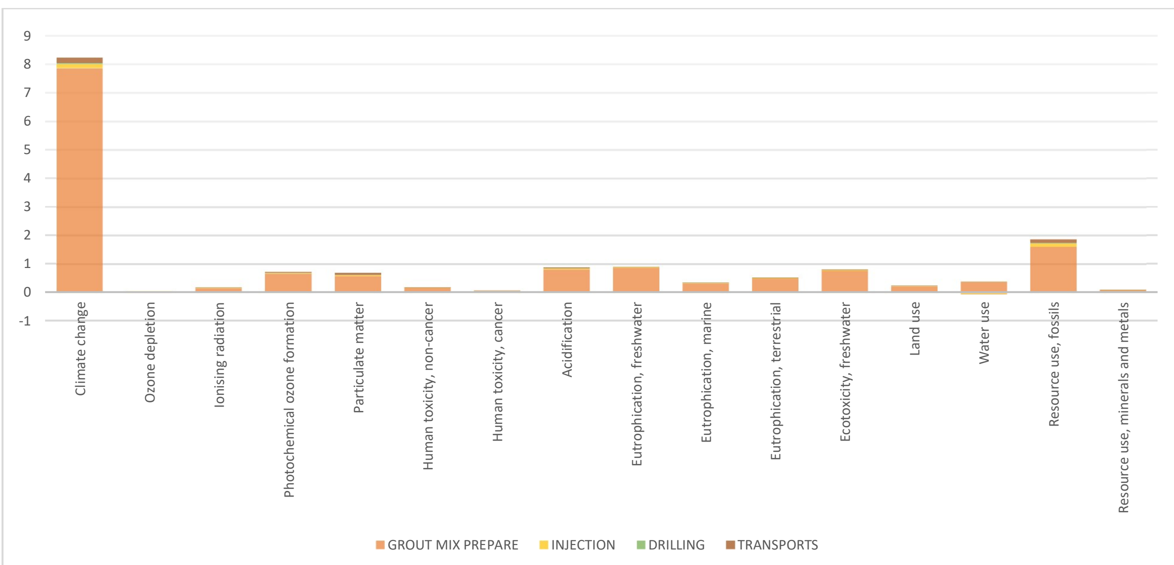


Fig. 8-21, Jet grouting with double fluid technique: impact, weighted view.

The single point plot exhibits similarities to the single fluid scenario, however with a 30% greater influence resulting from the grout mixing stages. The prominence of grout mixture influences the concealment of its impact, whereas the injection phase is concurrently experiencing a substantial increase in impact as a result of the requirement for more robust high-pressure systems.

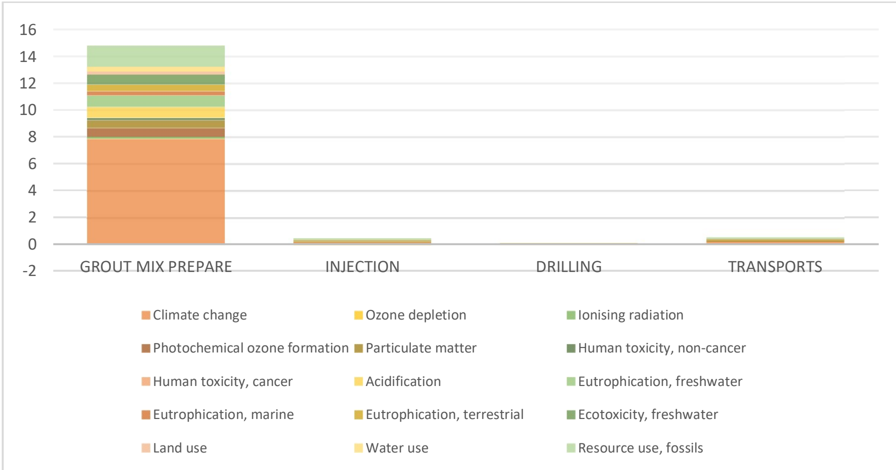


Fig. 8-22, Jet grouting with double fluid technique: impact, single score view.

Once more, the numerical results give more sight into the detail of impact percentages: 94.7% comes from the grout preparation phase, few points more than the single fluid case.

Impact category	Unit	Total	GROUT MIX PREPARATION	INJECTION	DRILLING	TRANSPORTATION
Total	%	100,0	94,7	2,1	0,4	2,7
Climate change	%	52,4	50,4	0,8	0,1	1,0
Ozone depletion	%	0,1	0,1	0,0	0,0	0,0
Ionising radiation	%	1,0	0,9	0,0	0,0	0,0
Photochemical ozone formation	%	4,5	4,2	0,1	0,0	0,2
Particulate matter	%	4,1	3,5	0,2	0,1	0,4
Human toxicity, non-cancer	%	1,0	1,0	0,0	0,0	0,0
Human toxicity, cancer	%	0,3	0,3	0,0	0,0	0,0
Acidification	%	5,5	5,1	0,2	0,0	0,1
Eutrophication, freshwater	%	5,1	5,0	0,1	0,0	0,0
Eutrophication, marine	%	2,2	2,0	0,1	0,0	0,1
Eutrophication, terrestrial	%	3,3	3,0	0,1	0,0	0,1
Ecotoxicity, freshwater	%	5,2	4,9	0,2	0,0	0,1
Land use	%	1,5	1,4	0,1	0,0	0,0
Water use	%	1,8	2,1	-0,3	0,0	0,0
Resource use, fossils	%	11,5	10,1	0,6	0,1	0,7
Resource use, minerals and metals	%	0,5	0,5	0,0	0,0	0,0

Tab. 8-16, Jet grouting with double fluid technique: impact percentages, single point view.

The following table presents the quantitative results of the Key Performance Indicator (KPI) characterisation.

Impact category	Unit	Total	GROUT MIX ONSITE	GROUT MIX INJECTION	DRILLING	MATERIAL AND EQUIPMENT TRANSPORTATION
Climate change	kg CO2 eq	384881,11190	370504,18160	5933,85681	1061,43874	7381,63475
Ozone depletion	kg CFC11 eq	0,01649	0,01352	0,00102	0,00024	0,00171
Ionising radiation	kBq U-235 eq	16427,32749	15259,96695	633,37203	64,79264	469,19588
Photochemical ozone formation	kg NMVOC eq	727,82150	674,01663	22,15360	7,03067	24,62059
Particulate matter	disease inc.	0,00525	0,00450	0,00021	0,00007	0,00048
Human toxicity, non-cancer	CTUh	0,00243	0,00233	0,00003	0,00000	0,00007
Human toxicity, cancer	CTUh	0,00004	0,00004	0,00000	0,00000	0,00000
Acidification	mol H+ eq	940,28272	877,69088	31,23462	5,79145	25,56577
Eutrophication, freshwater	kg P eq	56,42727	55,21239	1,17006	0,00727	0,03756
Eutrophication, marine	kg N eq	272,64744	253,76441	8,32506	2,35435	8,20361
Eutrophication, terrestrial	mol N eq	2968,13778	2769,17515	82,83944	25,88502	90,23817
Ecotoxicity, freshwater	CTUe	2211604,43314	2099513,03752	65116,98166	4940,25536	42034,15859
Land use	Pt	2867315,43898	2758965,16931	105438,95327	605,51049	2305,80592
Water use	m3 depriv.	47202,39712	54744,85318	-7524,67268	3,00501	-20,78839
Resource use, fossils	MJ	1712391,06681	1506762,46825	86456,86997	14602,90580	104568,82279
Resource use, minerals and metals	kg Sb eq	0,08396	0,07850	0,00448	0,00049	0,00051
Climate change - Fossil	kg CO2 eq	384090,76833	369741,75741	5906,45408	1061,35295	7381,20389
Climate change - Biogenic	kg CO2 eq	506,36111	482,54621	23,38793	0,06856	0,35841
Climate change - Land use and LU change	kg CO2 eq	283,98246	279,87798	4,01481	0,01722	0,07245

Tab. 8-17, Jet grouting with double fluid technique, impact percentages, characterization.

A detailed study was conducted for the subprocess to emphasize the function played by each component of the grout mix. The identical conclusion about the overall situation may be derived by examining the individual point plot pertaining to the concentrate on grout mix preparation. It is evident that cement is the primary driver of the affects.

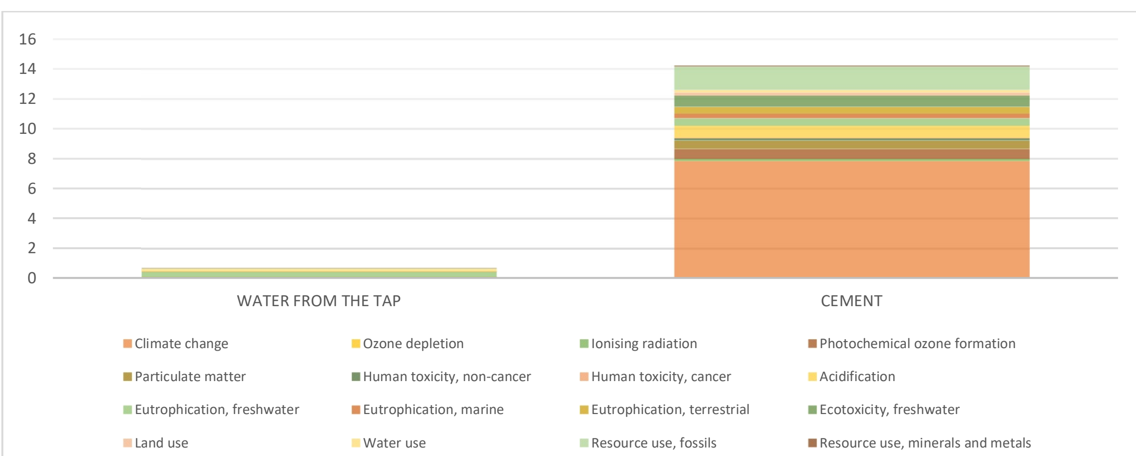


Fig. 8-23, Jet grouting with double fluid technique: grout mix preparation sub analysis, impact, characterization view.

8.8.3 Jet Grouting Double fluid sensitivity analysis

The requirements/suggestions coming from the qualitative assessment with Envision (i.e. the main leverages to focus on) are:

- Energy: Improve consumption (a) reducing power production from diesel engines, (b) using electricity coming from providers that use a mix of production that includes renewable sources.
- Transportation: Improving the rating of diesel transportation fueled trucks.
- Cement: reduce the content in clinker (through pozzolana or fly ash additions).

To the aim of including these sustainability upgrades with respect to the original LCA baseline just described in detail, another sensitivity run of the LCA model has been performed with these modifications:

- Energy: use an energy mix 70% fossil and 30% renewable (for instance hydro coming from run off river generation), through the Ecoinvent string: Electricity, high voltage {IT}| electricity production, hydro, run-of-river | APOS, U.
- Cement: use Pozzolana-based cement instead of Portland-based cement, through the Ecoinvent string: Cement, pozzolana and fly ash 11-35% {Europe without Switzerland}| market for cement, pozzolana and fly ash 11-35% | APOS, U.
- Steel: use iron coming from scrap, through the Ecoinvent string Iron scrap, unsorted {RoW}| steel production, electric, low-alloyed | APOS, U.
- Transportation: use trucks Euro6 instead of Euro5, through the Ecoinvent string: Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U.

The analysis provided is merely suggestive due to the inherent generality of the data sourced from the Ecoinvent database. However, further enhancements can be made by utilizing customized Environmental Product Declarations (EPDs) or material-specific Life Cycle Assessments (LCAs) offered by suppliers. Nevertheless, the sensitivity calculation presented can offer an estimation of the potential improvement in the sustainability performance of the technique, taking into account the recommendations derived from the Envision indicators.

The next table gives the raw characterization data for the sensitivity runs.

Impact category	Unit	Total	GROUT MIX ONSITE	GROUT MIX INJECTION	DRILLING	MATERIAL AND EQUIPMENT TRANSPORTATION
Climate change	kg CO2 eq	317711,94070	302260,17290	7184,21924	###	7206,10983
Ozone depletion	kg CFC11 eq	0,01432	0,01131	0,00109	###	0,00167
Ionising radiation	kBq U-235 eq	14234,40492	12811,15781	899,56071	###	458,89376
Photochemical ozone formation	kg NMVOC eq	587,47960	555,26164	15,83694	###	9,35036
Particulate matter	disease inc.	0,00438	0,00377	0,00013	###	0,00042
Human toxicity, non-cancer	CTUh	0,00202	0,00191	0,00004	###	0,00006
Human toxicity, cancer	CTUh	0,00004	0,00003	0,00000	###	0,00000
Acidification	mol H+ eq	776,69851	721,12876	35,51339	###	14,26493
Eutrophication, freshwater	kg P eq	51,01587	49,01057	1,96130	###	0,03674
Eutrophication, marine	kg N eq	221,46489	210,47957	6,25467	###	2,37631
Eutrophication, terrestrial	mol N eq	2388,48662	2276,17834	60,00236	###	26,42091
Ecotoxicity, freshwater	CTUe	1821227,78146	1680056,53433	94960,39462	###	41270,59712
Land use	Pt	2401473,87742	2221105,68448	177507,50501	###	2255,17744
Water use	m3 depriv.	44459,07300	49620,07971	-5143,67978	###	-20,33194
Resource use, fossils	MJ	1477694,64217	1253656,51352	107162,41409	###	102272,80866
Resource use, minerals and metals	kg Sb eq	0,07216	0,06490	0,00628	###	0,00050
Climate change - Fossil	kg CO2 eq	317043,97470	301639,03545	7137,89788	###	7205,68843
Climate change - Biogenic	kg CO2 eq	432,54448	392,56897	39,55641	###	0,35054
Climate change - Land use and LU change	kg CO2 eq	235,42151	228,56848	6,76495	###	0,07086

Tab. 8-18, Jet grouting with double fluid technique: sensitivity analysis based on materials, energy and transportation optimizations, impact indicators, characterization.

In the double fluid technique, the sensitivity allows for a reduction in CO2e of about 17% with respect to the baseline case.

Material/ Consumption	Quantity	Unit
Cement	425000	kg
Energy-Electricity	10998	kWh
Energy-Diesel	1050	kWh
Steel	0	kg
T.A.M.	0	kg
Sludge waste	283	m3
Water	425000	kg

Climate change	51,78%	317711,94034	384881,11064	kg CO2 eq	-17,45%
Ozone depletion	0,00%	0,01432	0,01649	kg CFC11 eq	-13,18%
Ionising radiation	0,00%	14234,40491	16427,32747	kBq U-235 eq	-13,35%
Photochemical ozone formation	4,33%	587,47960	727,82150	kg NMVOC eq	-19,28%
Particulate matter	4,13%	0,00438	0,00525	disease inc.	-16,66%
Human toxicity, non-cancer	0,00%	0,00202	0,00243	CTUh	-17,18%
Human toxicity, cancer	0,00%	0,00004	0,00004	CTUh	-17,39%
Acidification	5,43%	776,69851	940,28271	mol H+ eq	-17,40%
Eutrophication, freshwater	5,57%	51,01587	56,42727	kg P eq	-9,59%
Eutrophication, marine	0,00%	221,46489	272,64744	kg N eq	-18,77%
Eutrophication, terrestrial	0,00%	2388,48662	2968,13777	mol N eq	-19,53%
Ecotoxicity, freshwater	5,13%	1821227,77274	2211604,42657	CTUe	-17,65%
Land use	0,00%	2401473,86489	2867315,42743	Pt	-16,25%
Water use	0,00%	44459,07287	47202,39701	m3 depriv.	-5,81%
Resource use, fossils	11,85%	1477694,64211	1712391,06776	MJ	-13,71%
Resource use, minerals and metals	0,00%	0,07216	0,08396	kg Sb eq	-14,06%

Tab. 8-19, Jet grouting with double fluid technique: sensitivity analysis vs. baseline, total impact indicators, characterization.

8.9 LCA analysis for ground improvement treatment using ground freezing with brine

8.9.1 Input data

The following two ground improvement case studies refer to a technology different than the grout-based treatments described in the previous chapters: the artificial ground freezing (AGF) technique. In this case, the purpose is to generate a temporary mechanical and waterproofing improvement to the ground by freezing the water embedded in the soil below the water table for the time needed to excavate the rest of the structure.

Ground freezing can occur using the direct (with liquid nitrogen as a coolant) or indirect (with brine) method. For both systems, thermometric detection points (thermometers placed surrounding the volume to be frozen) allow the monitoring of the formation of the frozen structure up to achieving the required dimensions at the effective temperature.

In this case, the freezing ground treatment is implemented by placing 82 metallic freezing pipes in the ground, disposed on two rows per side, with an interaxis of 1,20 m between the pipes and 1,25 between the rows. The resulting ‘frozen wall’ has a thickness of 2.8m, which guarantees a total treated volume equal to 560m3.

A freezing probe is made up of two coaxial pipes (in this case, stainless steel has been adopted) connected at their top with a particular head. The coolant enters the inner pipe through the head, travels through the annular space between the two pipes, and then exits through a different connection on the particular head.

As the first case of AGF, the indirect method will be considered. Freezing occurs with refrigeration systems, where water and a calcium chloride solution (brine) at -35°C flow in a closed circuit. The freezing probes, previously installed in the ground, are part of the circuit, connected to a manifold by the particular head. The brine releases cryogenic energy to the ground and returns to the refrigerator unit, where it cools down again using a heat exchanger. A pump allows the continuous flowing of the brine in the circuit.

The pipes are installed in the ground (similarly to the PVC pipes for the permeation grouting) into drilled holes and embedded using a ternary grout (water, cement, and bentonite), thus filling the void annular space surrounding the probe, thus avoiding the reduction of the freezing efficiency.

The freezing process can be divided into two stages: the initial freezing stage, during which, around each freezing probe, the diameter of the single frozen soil columns increases until they join each other, thus creating a wall through a highly energy-intensive process. The design provides the thickness of the frozen wall and the target temperature to be achieved along its borders; the ground thermometers allow the monitoring of the treatment evolution.

In this case, the targets are a frozen wall thickness of 2,4 m with a temperature of – 4°C at the border, operating with the brine at -35°C. This first stage stops when the target is reached. In the considered condition, the freezing is completed in 30 days.

The second phase of the freezing is the maintenance stage, during which the shaft excavation and the concrete plate and walls are cast. The freezing plant operates with the brine at -28°C in order to keep the border of the efficient frozen wall at least at -4°C. A maintenance time of 30 days has been considered.

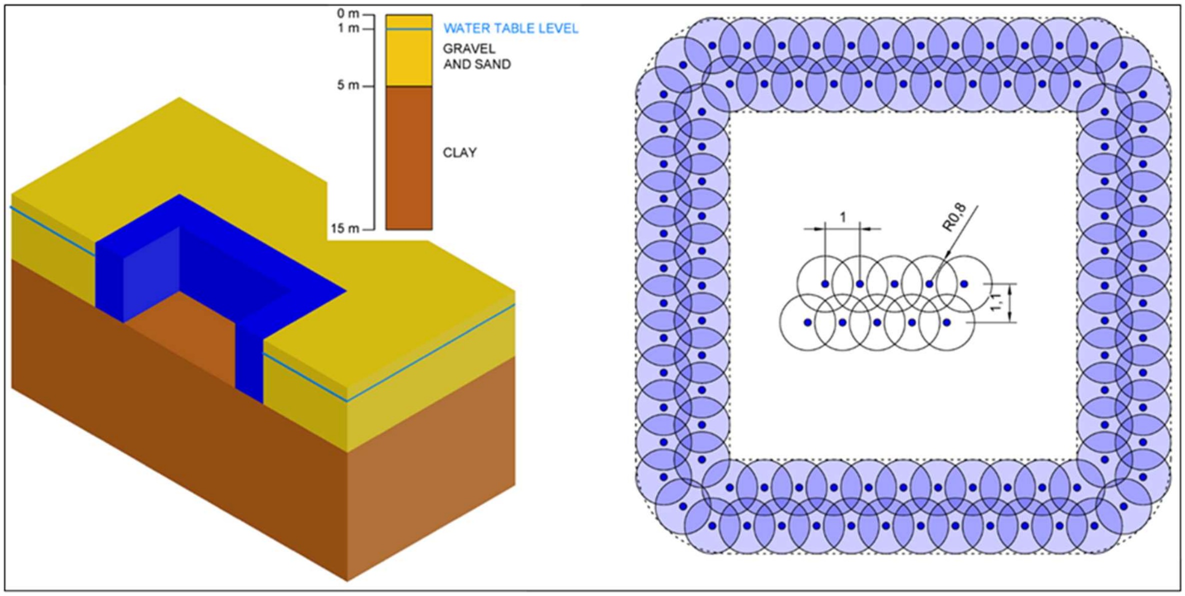


Fig. 8-24, Artificial ground freezing with brine technique: geometrical data.

The subsequent table presents the pertinent data for the life cycle assessment (LCA) study.

ITEM	INPUT	VALUE	UNIT	ECOINVENT DATABASE REFERENCE
Brine use	Product	4915	Mass (kg)	Sodium chloride, brine solution
	Transport	442350	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U (4915kg * 90km)
	Waste	4915	Mass (kg)	Wastewater, average {Europe without Switzerland}| market for wastewater, average | APOS, U
PVC pipes for thermal probes	Product	0.7	Mass (kg)	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | APOS, U
	Process	0.7	Mass (kg)	Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U
Thermocouples for thermal probes	Product	3.5	Mass (kg)	Copper {RER}| production, primary | APOS, U
	Transport	378	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U ((3.5+0.7)kg * 90km)
Diesel driller (for sheath)	Consumption	43.2	Duration (hr)	Machine operation, diesel, >= 74.57, underground mining (GLO), market for APOS, U
	Product	6500	Mass (kg)	/
	Transport	585000	Mass*Distance (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (6500kg * 90km)
Electric agitator (for sheath)	Consumption	2.2	Energy (kWh)	Electricity, medium voltage {IT}| market | APOS, U
	Product	350	Mass (kg)	/
	Transport	31500	Mass*Distance (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (350kg * 90km)
Electric injector (for sheath)	Consumption	44	Energy (kWh)	Electricity, medium voltage {IT}| market | APOS, U
	Product	600	Mass (kg)	/
	Transport	54000	Mass*Distance (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (600kg * 90km)
Cement	Product	2111	Mass (kg)	Cement, Portland {CH}| market for | APOS, U
	Transport	189990	Mass*Distance (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (2111kg * 90km)
Bentonite	Product	192	Mass (kg)	Bentonite {RoW}| quarry operation | APOS, U
	Transport	206*207 =42642	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U (192kg * 90km)
Water	Potable water from the tap	4094	Mass (kg)	Tap water {Europe without Switzerland}| market for | APOS, U
	Transport	0	Mass*Distance (kg*km)	/
Freezing probes	Product	4039	Mass (kg)	Steel, low-alloyed {GLO}| market for | APOS, U
	Process	4039	Mass (kg)	Sheet rolling, steel {RER}| processing | APOS, U
	Product	120	Mass (kg)	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | APOS, U
	Process	120	Mass (kg)	Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U
	Transport	374310	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U ((4039+120)kg * 90km)
Connection pipe between freezing probes. Steel pipe and thermal insulation	Product (steel)	581	Mass (kg)	Steel, low-alloyed {GLO}| market for | APOS, U
	Process	581	Mass (kg)	Sheet rolling, steel {RER}| processing | APOS, U
	Product (insul.)	58	Mass (kg)	Synthetic rubber {RER}| production | APOS, U
	Process	58	Mass (kg)	Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U
	Transport	57510	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport| APOS, U ((581+58)kg * 90km)
Connection brine tank with probes network. Steel pipe and thermal insulation	Product (steel)	1210	Mass (kg)	Steel, low-alloyed {GLO}| market for | APOS, U
	Process	1210	Mass (kg)	Sheet rolling, steel {RER}| processing | APOS, U
	Product (insul)	120	Mass (kg)	Synthetic rubber {RER}| production | APOS, U
	Process	120	Mass (kg)	Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U
	Transport	119700	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U ((1210+120)kg * 90km)
Refrigeration for brine freezing first time	Consumption	48886	Energy (kWh)	Electricity, medium voltage {IT}| market for | APOS, U
Refrigeration for brine freezing maintenance	Consumption	29331	Energy (kWh)	Electricity, medium voltage {IT}| market for | APOS, U

Tab. 8-20, Artificial ground freezing with brine technique: LCA analysis input data.

The equipment and overall system used for implementing ground freezing with brine appear to be significantly more intricate in their appearance compared to earlier instances. However, as will be demonstrated shortly, the overall sustainability performance appears to be rather interesting.

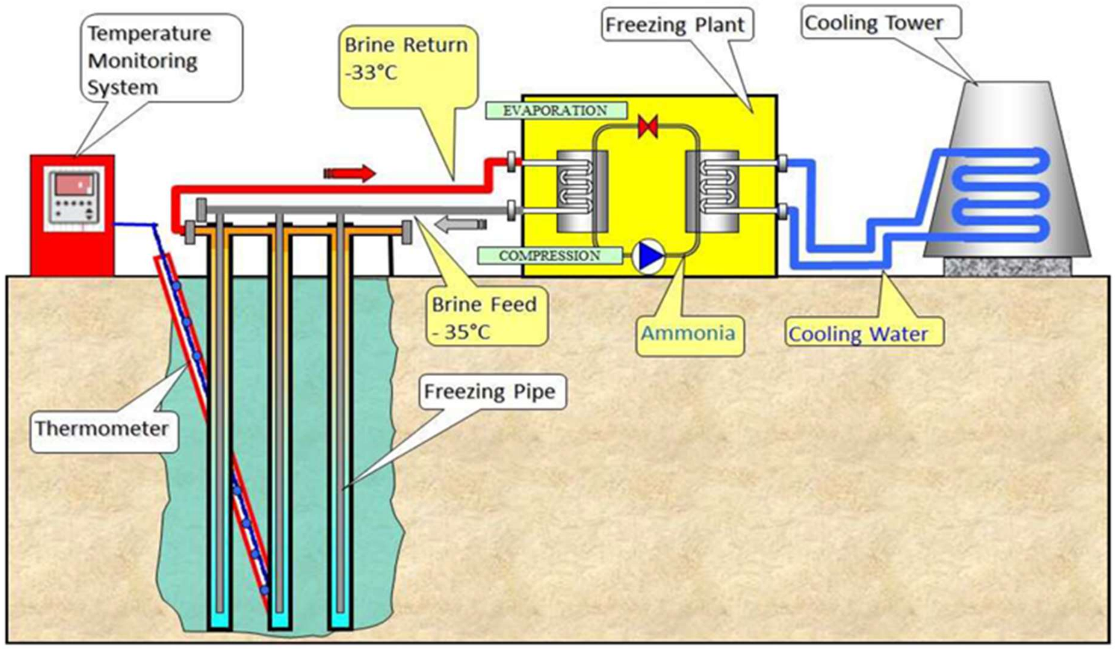


Fig. 8-25, Artificial ground freezing with brine technique: Indirect system circuit scheme (with brine) (Rodio Geotechik AG website and Mira-Cattò et al. (2016)).

The following diagram illustrates how the ground freezing with brine technology works in terms of its process flows.

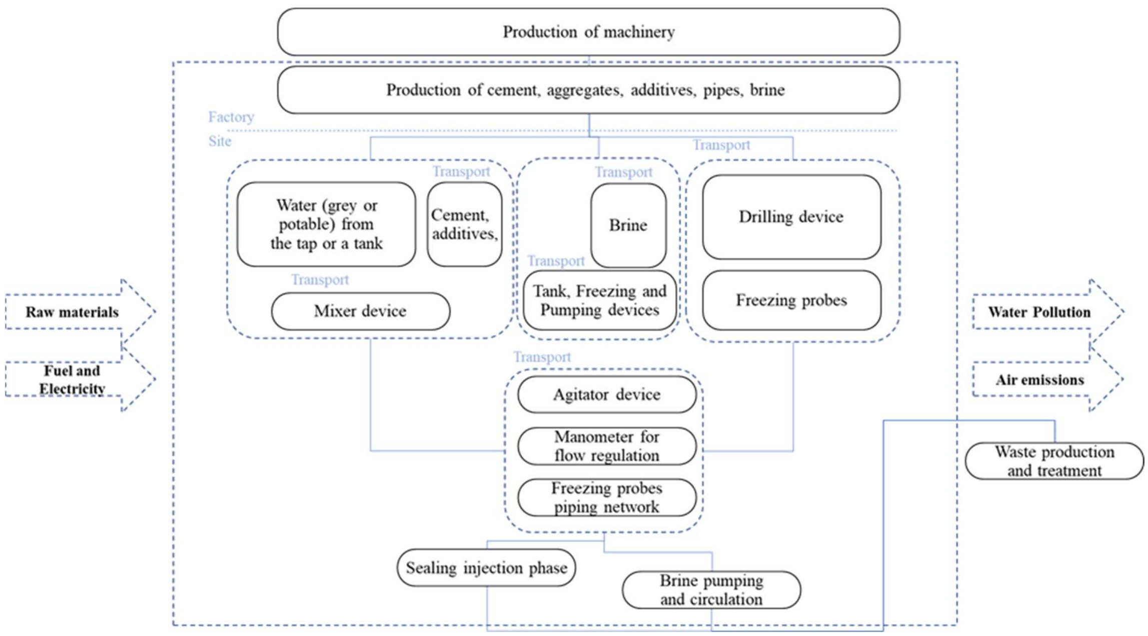


Fig. 8-26, Artificial ground freezing with brine technique: Process scheme for LCA Analysis.

8.9.2 Ground freezing with brine LCA analysis

The ground freezing technique, which is usually considered challenging for its complexity, the duration of the treatment, and the need for a better knowledge of soil characteristics, comes here in a completely different light (the light of environmental sustainability). Among this technique, it is interesting to analyze the direct (brine) versus the indirect (liquid nitrogen) approach. We begin with the indirect approach that uses brine as a freezing medium.

One notable distinction in comparison to the preceding instances is already evident from the characterization plot: the significance of impact is mostly divided between the freezing phase and the drilling phase.

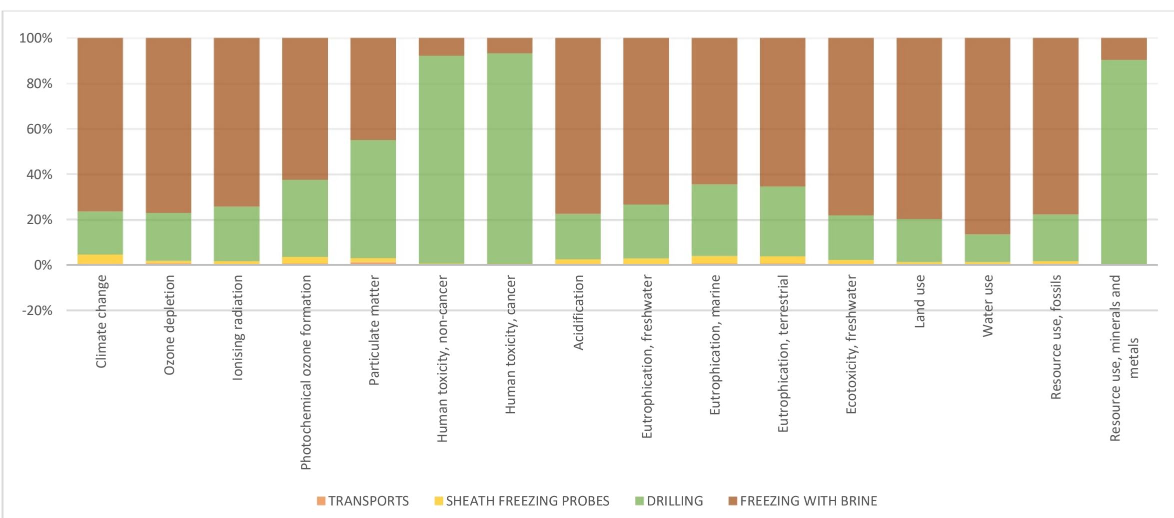


Fig. 8-27, Artificial ground freezing with brine technique: impact, characterization view.

It is evident that the set of freezing probes and the interconnecting pipes between them have a more substantial influence on the overall effect when compared to the other subprocesses, namely the impacts associated with material, drilling, and sheath mix generation. However, in addition, the contribution of the refrigeration system is also appreciable (energy related impacts).

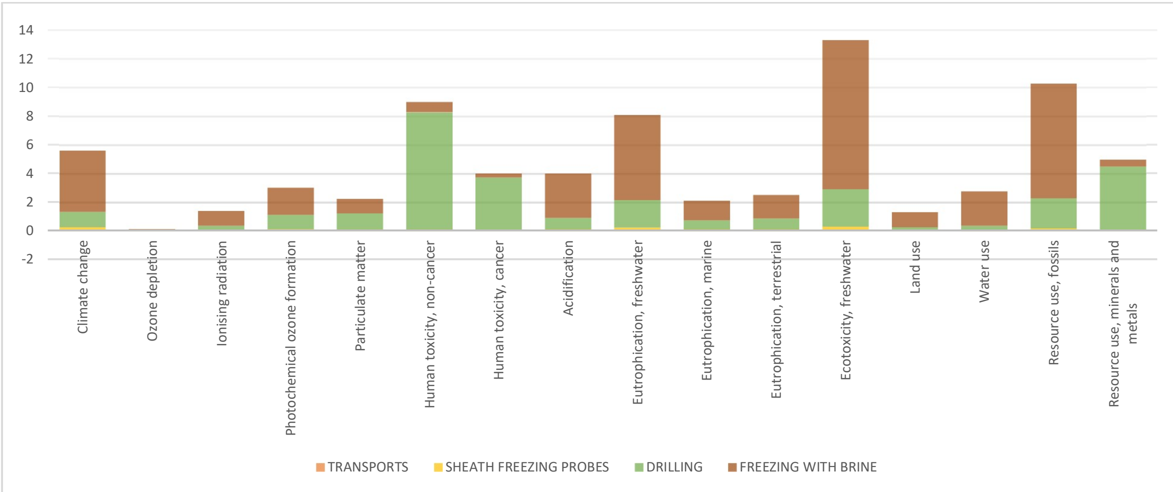


Fig. 8-28, Artificial ground freezing with brine technique: impact, normalization view.

As it can be seen in the following figure, the freezing phase plays the most relevant role in the weighting plot due to its energy needs.

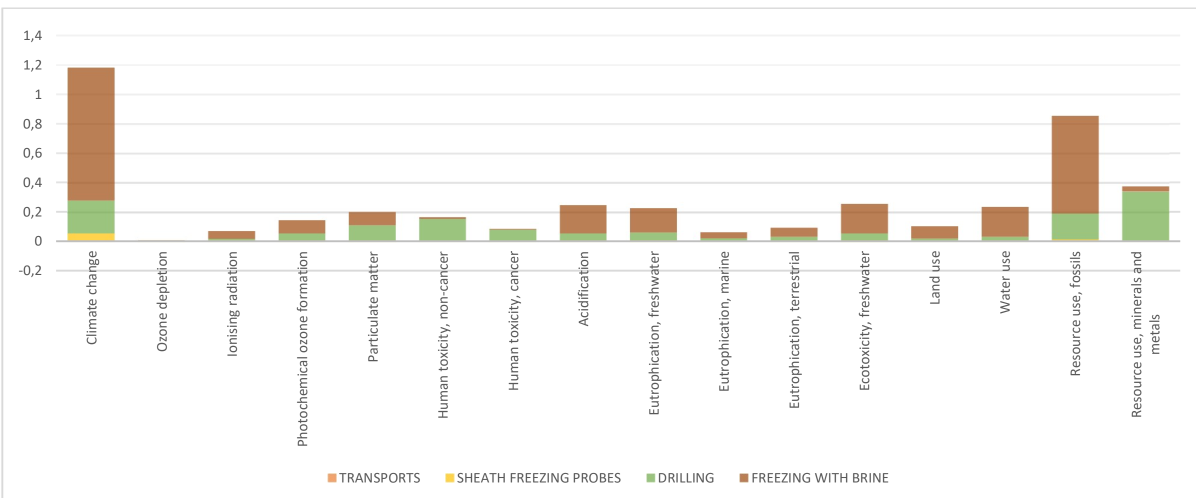


Fig. 8-29, Artificial ground freezing with brine technique: impact, weighted view.

The final single point scores set the balance between the phases, with the freezing phase that has a double impact with respect to the drilling phase.

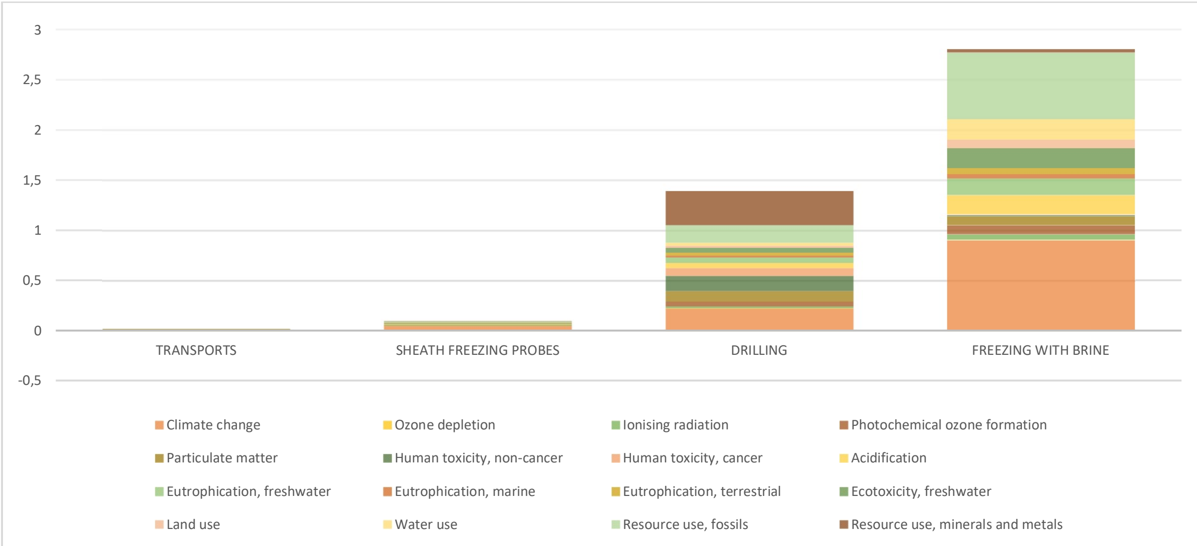


Fig. 8-30, Artificial ground freezing with brine technique: impact, single score view.

There are two conclusions that may be derived with respect to the technological aspect of artificial freezing through the utilization of brine.

- The phase that has the most influence is the freezing process involving brine, where the fluid must be continuously circulated and operational during the excavation activities.
- The drilling phase has significant importance primarily in the context of steel production for the network of probes, contributing to about one-third of the entire impact. This impact is mostly focused in the depletion of resources.

The next table shows the single point results in terms of percentage: the freezing phase scores 65,1% of the impacts while drilling positions around 32,2%.

Impact category	Unit	Total	TRANSPORTATION	SHEATH	DRILLING PROBES	FREEZING WITH BRINE
Total	%	100,0	0,4	2,2	32,2	65,1
Climate change	%	27,4	0,1	1,1	5,2	20,9
Ozone depletion	%	0,2	0,0	0,0	0,0	0,1
Ionising radiation	%	1,6	0,0	0,0	0,4	1,2
Photochemical ozone formation	%	3,3	0,0	0,1	1,1	2,1
Particulate matter	%	4,7	0,1	0,1	2,4	2,1
Human toxicity, non-cancer	%	3,8	0,0	0,0	3,5	0,3
Human toxicity, cancer	%	2,0	0,0	0,0	1,8	0,1
Acidification	%	5,7	0,0	0,1	1,2	4,5
Eutrophication, freshwater	%	5,3	0,0	0,2	1,2	3,9
Eutrophication, marine	%	1,4	0,0	0,0	0,5	0,9
Eutrophication, terrestrial	%	2,2	0,0	0,1	0,7	1,4
Ecotoxicity, freshwater	%	5,9	0,0	0,1	1,2	4,6
Land use	%	2,4	0,0	0,0	0,5	1,9
Water use	%	5,5	0,0	0,1	0,7	4,7
Resource use, fossils	%	19,8	0,1	0,2	4,1	15,4
Resource use, minerals and metals	%	8,7	0,0	0,0	7,8	0,8

Tab. 8-21, Artificial ground freezing with brine technique: impact percentages, single point view.

The next table shows the characterization raw data for the KPIs of each impact category.

Impact category	Unit	Total	MATERIAL AND EQUIPMENT TRANSPORTATION	SHEATH ON SITE	DRILLING AND PIPES	BRINE FREEZING
Climate change	kg CO2 eq	45377,18315	242,7359361	1877,243278	8585,983881	34671,22006
Ozone depletion	kg CFC11 eq	0,006848155	5,61407E-05	7,26463E-05	0,001444037	0,005275331
Ionising radiation	kBq U-235 eq	5918,79628	15,38263566	82,07437996	1423,606748	4397,732517
Photochemical ozone formation	kg NMVOC eq	122,4566282	0,803212783	3,473374011	41,66019995	76,51984147
Particulate matter	disease inc.	0,001330483	1,67876E-05	2,40639E-05	0,00069076	0,000598872
Human toxicity, non-cancer	CTUh	0,002061765	2,40537E-06	1,18214E-05	0,001885232	0,000162307
Human toxicity, cancer	CTUh	6,75877E-05	1,97561E-08	2,08519E-07	6,27511E-05	4,60835E-06
Acidification	mol H+ eq	221,8682917	0,835449234	4,573101534	44,67554044	171,7842005
Eutrophication, freshwater	kg P eq	12,98631933	0,00123149	0,375140148	3,079358082	9,530589613
Eutrophication, marine	kg N eq	41,12720569	0,267496982	1,345759929	13,00799953	26,50594925
Eutrophication, terrestrial	mol N eq	443,2854945	2,941807814	14,25495559	136,288264	289,8004671
Ecotoxicity, freshwater	CTUe	567979,1944	1400,813236	11109,02558	111788,5785	443680,777
Land use	Pt	1073906,938	75,5960863	14607,63262	202643,3999	856580,3093
Water use	m3 depriv.	31698,83098	-0,681549364	422,1306245	3859,258216	27418,12369
Resource use, fossils	MJ	667564,1661	3428,299718	8045,791087	137221,7437	518868,3315
Resource use, minerals and metals	kg Sb eq	0,316177939	1,66179E-05	0,000704961	0,284793487	0,030662873
Climate change - Fossil	kg CO2 eq	45124,86041	242,7218103	1873,181369	8561,034541	34447,92269
Climate change - Biogenic	kg CO2 eq	209,8059394	0,011750481	2,634568781	16,68773293	190,4718872
Climate change - Land use and LU change	kg CO2 eq	42,5168036	0,002375362	1,427340138	8,261607607	32,82548049

Tab. 8-22, Artificial ground freezing with brine technique: impact percentages, characterization.

8.9.3 Brine freezing sensitivity analysis

The requirements/suggestions coming from the qualitative assessment with Envision (i.e. the main leverages to focus on) are:

- Energy: Improve consumption (a) reducing power production from diesel engines, (b) using electricity coming from providers that use a mix of production that includes renewable sources.
- Transportation: Improving the rating of diesel transportation fueled trucks.
- Cement: reduce the content in clinker (through pozzolana or fly ash additions).

To the aim of including these sustainability upgrades with respect to the original LCA baseline just described in detail, another sensitivity run of the LCA model has been performed with these modifications:

- Energy: use an energy mix 70% fossil and 30% renewable (for instance hydro coming from run off river generation), through the Ecoinvent string: Electricity, high voltage {IT}| electricity production, hydro, run-of-river | APOS, U.
- Cement: use Pozzolana-based cement instead of Portland-based cement, through the Ecoinvent string: Cement, pozzolana and fly ash 11-35% {Europe without Switzerland}| market for cement, pozzolana and fly ash 11-35% | APOS, U.
- Steel: use iron coming from scrap, through the Ecoinvent string Iron scrap, unsorted {RoW}| steel production, electric, low-alloyed | APOS, U.
- Transportation: use trucks Euro6 instead of Euro5, through the Ecoinvent string: Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U.

As for the previous cases, the analysis is only indicative, because of the 'generic' nature of the data coming from the Ecoinvent database, and more could be done using customized EPDs or material oriented LCAs provided by suppliers, still this sensitivity calculation can give a measure of how much the sustainability performance of the technique could be improved in the light of the suggestions coming from the Envision indicators.

Impact category	Unit	Total	MATERIAL AND EQUIPMENT TRANSPORTATION	SHEATH ON SITE	DRILLING AND PIPES	BRINE FREEZING
Climate change	kg CO2 eq	33378,19348	235,598208	1531,0739	7269,934871	24341,5865
Ozone depletion	kg CFC11 eq	0,00506975	5,51578E-05	6,05916E-05	0,001253951	0,00370005
Ionising radiation	kBq U-235 eq	4048,455192	15,11329423	69,00812	862,4393749	3101,894403
Photochemical ozone formation	kg NMVOC eq	92,56538386	0,307002704	2,867628884	35,66509601	53,72565626
Particulate matter	disease inc.	0,000936553	1,46919E-05	2,03252E-05	0,00048016	0,000421376
Human toxicity, non-cancer	CTUh	0,000771164	2,23767E-06	9,70046E-06	0,000645037	0,000114189
Human toxicity, cancer	CTUh	2,95595E-05	1,79687E-08	1,74147E-07	2,61187E-05	3,24872E-06
Acidification	mol H+ eq	161,3159933	0,469318642	3,759808195	36,45412085	120,6327456
Eutrophication, freshwater	kg P eq	9,081065135	0,001209927	0,342375539	2,019494024	6,717985646
Eutrophication, marine	kg N eq	31,09724952	0,077992434	1,125266613	11,26099949	18,63299098
Eutrophication, terrestrial	mol N eq	333,1639604	0,866474537	11,74603604	117,1154798	203,4359701
Ecotoxicity, freshwater	CTUe	412217,0818	1380,838357	8933,400654	90437,50668	311465,3361
Land use	Pt	785600,0187	74,27244042	11757,3747	173634,7601	600133,6115
Water use	m3 depriv.	21746,53226	-0,669615808	390,8517903	2486,777217	18869,57287
Resource use, fossils	MJ	484622,7724	3368,27208	6681,009725	110120,5609	364452,9297
Resource use, minerals and metals	kg Sb eq	0,246833485	1,63269E-05	0,000631147	0,22454543	0,021640582
Climate change - Fossil	kg CO2 eq	33199,68553	235,5843295	1527,760287	7251,290541	24185,05037
Climate change - Biogenic	kg CO2 eq	147,7653661	0,011544737	2,147911009	12,16406929	133,4418411
Climate change - Land use and LU change	kg CO2 eq	30,74258691	0,002333771	1,16570245	6,480260544	23,09429015

Tab. 8-23, Artificial ground freezing with brine technique: sensitivity analysis based on materials, energy and transportation optimizations, impact indicators, characterization.

And finally, the comparison between the baseline of the LCA analysis and the sensitivity runs. The improvement with the sustainability countermeasures explained above is very relevant: about 26% reduction impact for CO2e.

Material/ Consumption	Quantity	Unit
Cement	2111	kg
Energy-Electricity	78278,6	kWh
Energy-Diesel	3240	kWh
Steel	5830	kg
T.A.M.	0	kg
Bentonite	192	kg
Brine waste	4915	kg
Sludge waste	0	m3
Water	4094	0

	Weighted single score	Total Sensitivity	Total Baseline	Unit	S/B
Climate change	28,35%	33378,19348	45377,18315	kg CO2 eq	-26,44%
Ozone depletion	0,00%	0,00507	0,00685	kg CFC11 eq	-25,97%
Ionising radiation	0,00%	4048,45519	5918,79628	kBq U-235 eq	-31,60%
Photochemical ozone formation	0,00%	92,56538	122,45663	kg NMVOC eq	-24,41%
Particulate matter	4,60%	0,00094	0,00133	disease inc.	-29,61%
Human toxicity, non-cancer	0,00%	0,00077	0,00206	CTUh	-62,60%
Human toxicity, cancer	0,00%	0,00003	0,00007	CTUh	-56,26%
Acidification	5,88%	161,31599	221,86829	mol H+ eq	-27,29%
Eutrophication, freshwater	5,17%	9,08107	12,98632	kg P eq	-30,07%
Eutrophication, marine	0,00%	31,09725	41,12721	kg N eq	-24,39%
Eutrophication, terrestrial	0,00%	333,16396	443,28549	mol N eq	-24,84%
Ecotoxicity, freshwater	6,06%	412217,08182	567979,19438	CTUe	-27,42%
Land use	0,00%	785600,01874	1073906,93792	Pt	-26,85%
Water use	5,27%	21746,53226	31698,83098	m3 depriv.	-31,40%
Resource use, fossils	20,25%	484622,77241	667564,16608	MJ	-27,40%
Resource use, minerals and metals	9,56%	0,24683	0,31618	kg Sb eq	-21,93%

Tab. 8-24, Artificial ground freezing with brine technique: sensitivity analysis vs. baseline, total impact indicators, characterization.

8.10 LCA analysis for ground improvement treatment using ground freezing with nitrogen

8.10.1 Input data

The last case study pertains to the utilization of artificial ground freezing (AGF) through the implementation of the 'direct technique'. The present methodology employs Liquid Nitrogen (LN) as a coolant. Liquid nitrogen (LN) is transported to the site by tank trucks and is introduced into the circuit at a temperature of approximately -196°C. The system consists of insulated steel tubing and a manifold that facilitates the transfer of coolant to the freezing probes. The former and the latter are indistinguishable when employed or utilized with brine. The liquid nitrogen (LN), when it enters the probes that are inserted into the ground, undergoes an increase in temperature and transitions into a gaseous state by evaporation. During the process of changing states, nitrogen exhibits a pronounced cryogenic effect and induces a thermal shock in the surrounding environment. This results in a significantly faster freezing rate compared to the utilization of a brine system. The nitrogen gas, which is depleted in energy and emanates from the probes at a temperature of -70°C, is afterwards collected and discharged into the atmosphere through a chimney using the direct Atmospheric Gas Flushing (AGF) technique. The process is overseen through the monitoring of ground temperature changes, which are measured by thermometric sensors. Additionally, an automatic system of electro-valves is utilized to regulate the supply of liquid nitrogen to each probe. This regulation is based on the return gas temperature from each pipe, with the aim of optimizing nitrogen consumption.

Regarding our case study, during the freezing stage, there is a significant flow of liquid nitrogen (LN) for a duration of around 8 days. It has been calculated that the theoretical frozen soil volume consumes 1,600 liters of LN per cubic meter. Subsequently, the system transitions into the maintenance phase for a duration of 30 days, coinciding with the excavation and execution of the construction. During this particular phase, nitrogen is introduced into the open circuit every two nights, owing to the notable efficiency of the LN AGF process. It is important to note that, as a general rule, working on the freezing site during the circulation of liquid nitrogen is often prohibited due to safety concerns. Specifically, a potential rupture in the circuit might result in the dispersion of nitrogen gas, which is denser than air and has the potential to rapidly deplete the oxygen content in the immediate work area. The nitrogen consumption rate for the maintenance stage is estimated to be 50 liters per cubic meter per day.

The inventory data required for the LCA analysis in this case study are as follows.

EM	INPUT	VALUE	UNIT	SIMAPRO ECOINVENT 3 IDENTIFIER
Liquid nitrogen (initial freezing)	Product	917.7	Mass (kg)	Nitrogen, liquid {RER}| market for | APOS, U (1600lt/m3 * 717m3 frozen ground * 0.8kg/m3 density / 1000)
	Transport	917.7*90 =82620	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U (716.8kg * 90km)
	Waste	917.7	Mass (kg)	Nitrogen, atmospheric
Liquid nitrogen (maintenance freezing, 30dd)	Product	860.4	Mass (kg)	Nitrogen, liquid {RER}| market for | APOS, U (50lt/m3/dd * 717m3 frozen ground * 0.8kg/m3 density / 1000 * 30dd)
	Transport	77436	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}| transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U (860.4kg * 90km)
	Waste	860.4	Mass (kg)	Nitrogen, atmospheric
PVC pipes for thermal probes	Product	0.7	Mass (kg)	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | APOS, U
	Process	0.7	Mass (kg)	Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U
Thermocouples for thermal probes	Product	3.5	Mass (kg)	Copper {RER}| production, primary | APOS, U
	Transport	(6.6+2.8)*30 =281.5	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U ((0.7+3.5) * 90km)
Diesel drilling machinery	Consumption	3240	Duration (hr)	Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| machine operation, diesel, >= 74.57 kW, steady-state | APOS, U (32hr * 1.35)
	Product	6500	Mass (kg)	/
	Transport	585000	Mass*Distance (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (6500kg * 90km)
Electric agitator (for sheath)	Consumption	17.6	Energy (kWh)	Electricity, medium voltage {IT}| market | APOS, U (2.2kW * 8hr)
	Product	350	Mass (kg)	/
	Transport	31500	Mass*Distance (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (350kg * 90km)
Electric injector (for sheath)	Consumption	44	Energy (kWh)	Electricity, medium voltage {IT}| market | APOS, U (5.5kW * 8hr)
	Product	600	Mass (kg)	/
	Transport	54000	Mass*Distance (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (600kg * 90km)
Cement (for sheath)	Product	2111	Mass (kg)	Cement, Portland {CH}| market for | APOS, U
	Transport	189990	Mass*Distance (kg*km)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | APOS, U (2111kg * 90km)
Bentonite (for sheath)	Product	192	Mass (kg)	Bentonite {RoW}| quarry operation | APOS, U
	Transport	17280	Mass*Distance (kg*km)	Transport, freight, lorry 3.5-7.5 metric ton, euro5 {RER}| market for transport, freight, lorry 3.5-7.5 metric ton, EURO5 | APOS, U (192kg * 90km)
Water (for sheath)	Water (potable) from the tap	4094	Mass (kg)	Tap water {Europe without Switzerland}| market for | APOS, U
	Transport	0	Mass*Distance (kg*km)	/
Freezing probes	Product	4039	Mass (kg)	Steel, low-alloyed {GLO}| market for | APOS, U
	Process	4039	Mass (kg)	Sheet rolling, steel {RER}| processing | APOS, U
	Transport	363510	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U (4039kg * 90km)
Probe connection pipe network. Steel pipes (stainless steel) wrapped in thermal insulation	Product (steel)	581	Mass (kg)	Steel, low-alloyed {RER}| steel production, electric, low-alloyed | APOS, U
	Process	581	Mass (kg)	Sheet rolling, steel {RER}| processing | APOS, U
	Product (insul.)	57.6	Mass (kg)	Synthetic rubber {RER}| production | APOS, U
	Process	57.6	Mass (kg)	Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U
	Transport	57474	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport,| APOS, U (581+57.6)kg * 90km)
Connection between probes and nitrogen tank. Steel pipe (stainless steel) wrapped in thermal insulation	Product (steel)	1210	Mass (kg)	Steel, low-alloyed {GLO}| market for | APOS, U
	Process	1210	Mass (kg)	Sheet rolling, steel {RER}| processing | APOS, U
	Product (insul.)	120	Mass (kg)	Synthetic rubber {RER}| production | APOS, U
	Process	120	Mass (kg)	Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U

	Transport	119700	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U ((1210+120)kg * 90km)
Connection between probes and nitrogen chimney. Steel pipe (stainless steel) wrapped in thermal insulation	Product (steel)	1210	Mass (kg)	Steel, low-alloyed {GLO}| market for | APOS, U
	Process	1210	Mass (kg)	Sheet rolling, steel {RER}| processing | APOS, U
	Product (insul.)	120	Mass (kg)	Synthetic rubber {RER}| production | APOS, U
	Process	120	Mass (kg)	Extrusion, plastic pipes {RER}| extrusion, plastic pipes | APOS, U
Nitrogen discharge chimney (steel)	Product	10	Mass (kg)	Steel, low-alloyed {GLO}| market for | APOS, U
	Process	10	Massa (kg)	Sheet rolling, steel {RER}| processing | APOS, U
	Transport	900	Mass*Distance (kg*km)	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport | APOS, U (10kg * 90km)

Tab. 8-25, Artificial ground freezing with nitrogen technique: LCA analysis input data for freezing with liquid nitrogen.

The equipment set, described in the following figure, that is needed for the AGF direct technique is simpler than the one used for the technique with brine; nitrogen is transported to the site and directly ‘injected’ in the network.

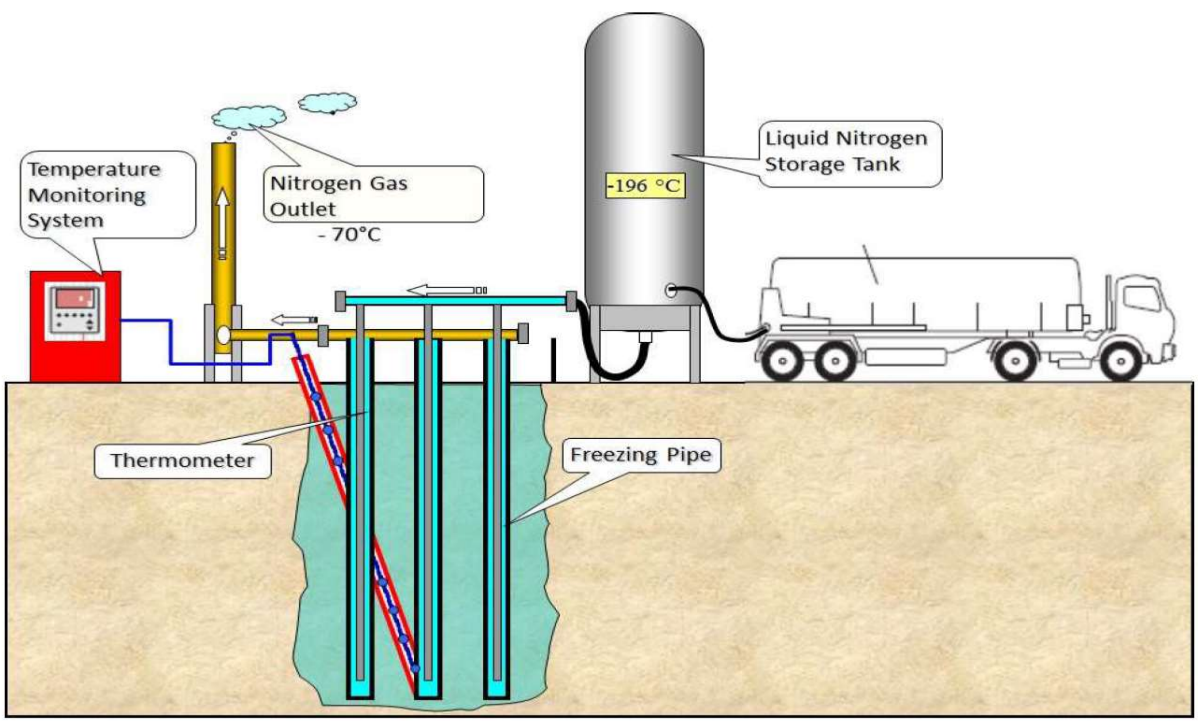


Fig. 8-31, Artificial ground freezing with nitrogen technique: direct system circuit scheme (Rodio Geotechik AG website and Mira-Cattò et al. (2016)).

The provided diagram illustrates the process scheme of the Life Cycle Assessment (LCA) model, showcasing the material and energy flows inside the building site and the defined limits, in addition to the functional unit.

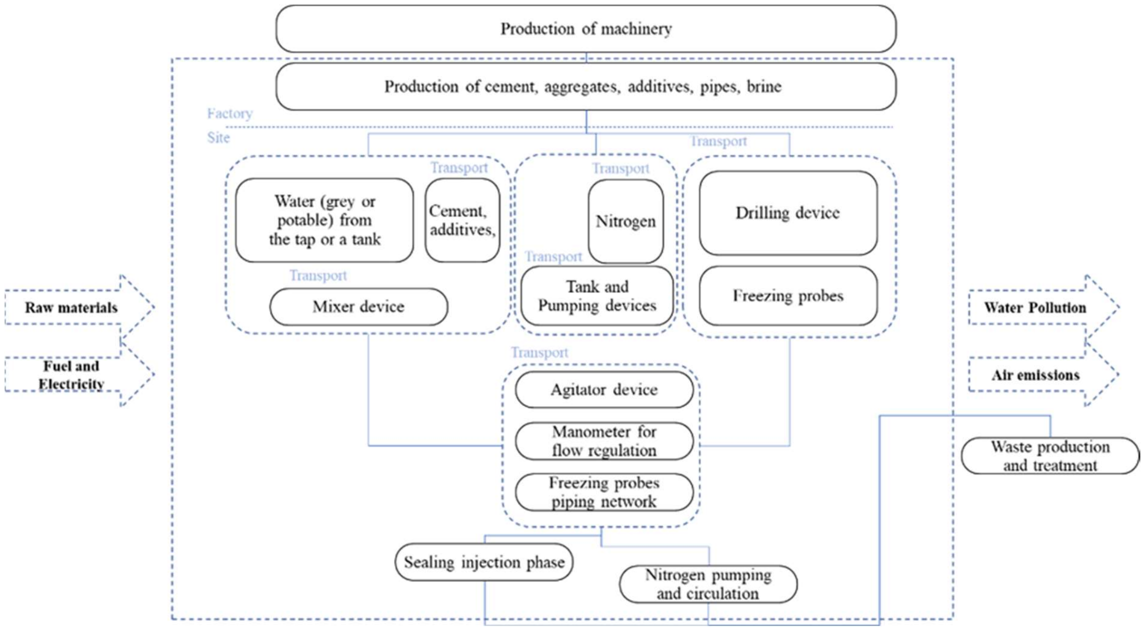


Fig. 8-32, Artificial ground freezing with nitrogen technique: LCA Process scheme.

8.10.2 Ground freezing with nitrogen LCA analysis

The utilization of nitrogen in ground freezing, namely in the indirect approach, is anticipated to result in a decreased overall effect compared to the use of brine due to the significant decrease in equipment requirements.

The primary focus of characterization plot is in the drilling phase, namely in relation to the materials used in the pipe network and the energy required for drilling, since these factors have the most significance in terms of their implications.

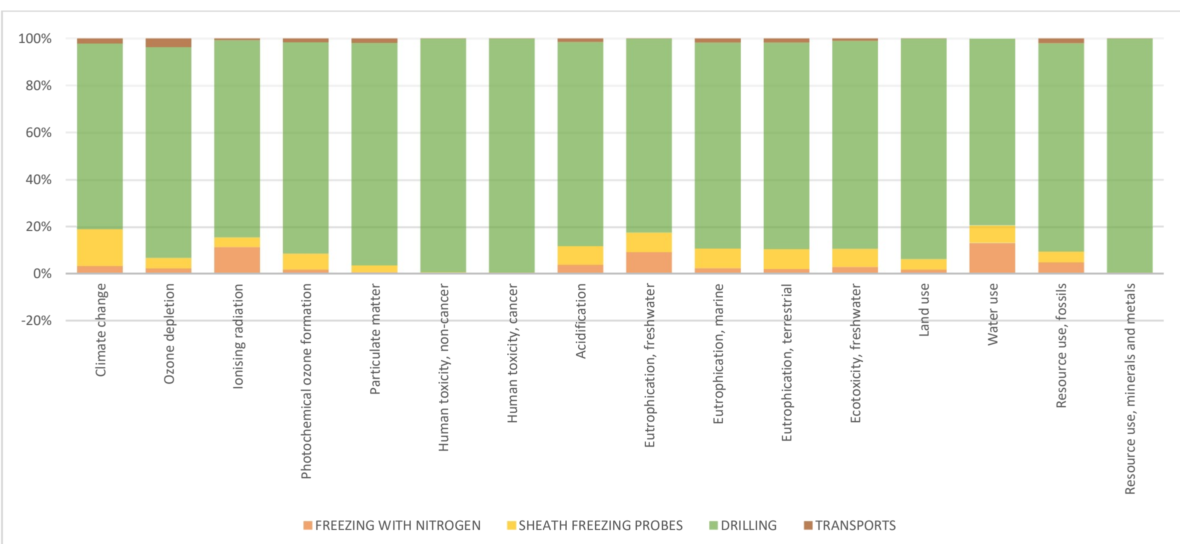


Fig. 8-33, Artificial ground freezing with nitrogen technique: impact, characterization view.

The highlighted categories that have been normalized pertain to the steel production process and the energy consumption associated with drilling equipment. The phenomenon of weighted perspectives has similar characteristics.

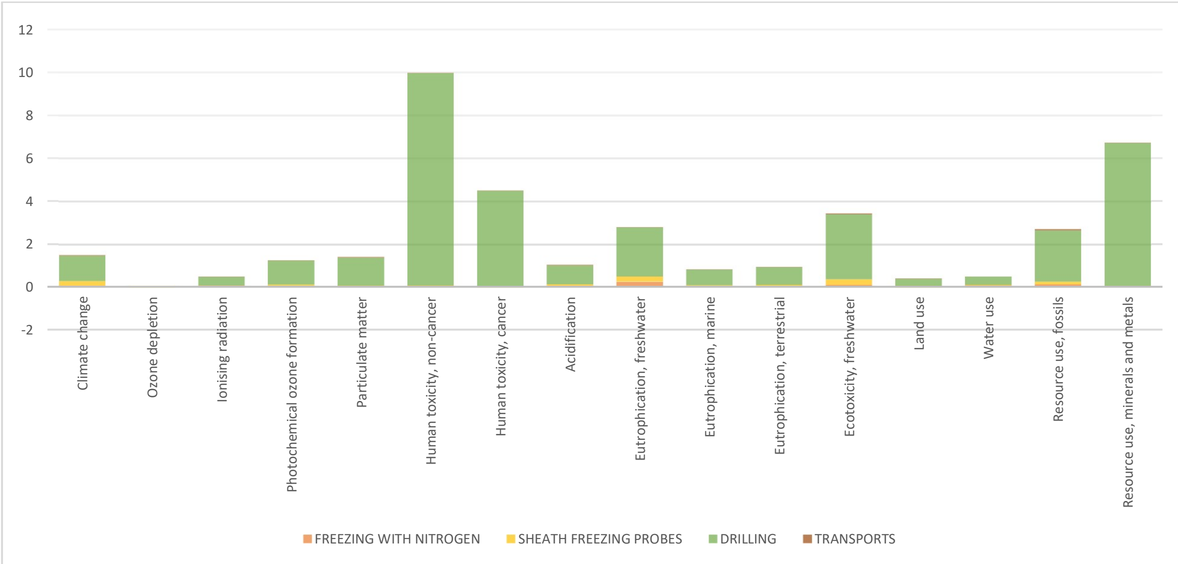


Fig. 8-34, Artificial ground freezing with nitrogen technique: impact, normalized view.

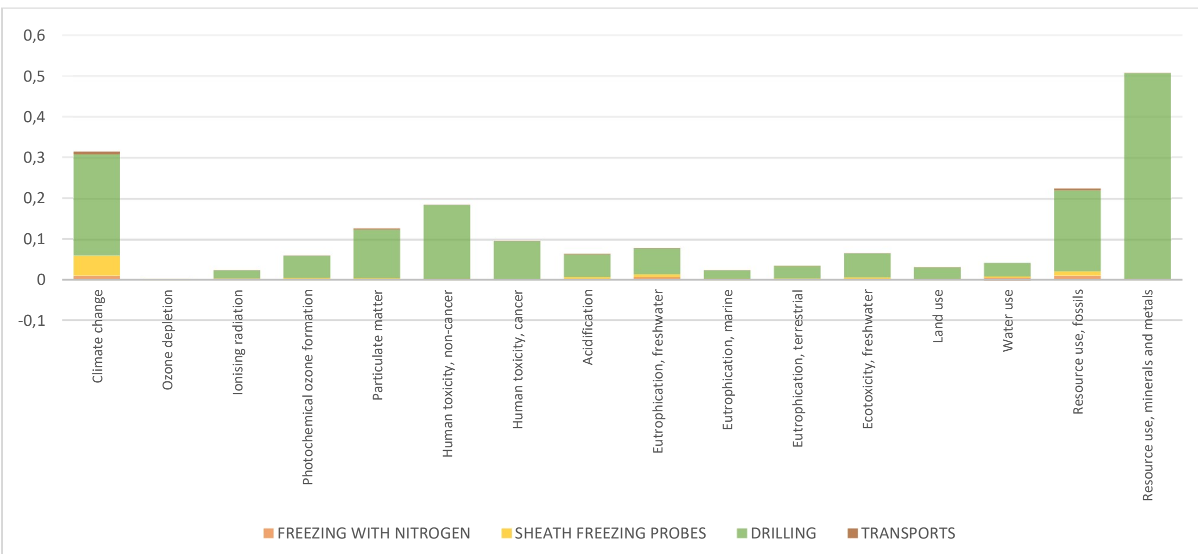


Fig. 8-35, Artificial ground freezing with nitrogen technique: impact, weighted view.

The analysis reveals that the drilling and sheath production categories have the most significance in terms of their influence. Notably, the primary factors contributing to this impact are climate change and the utilization of mineral, metal, and fossil resources.

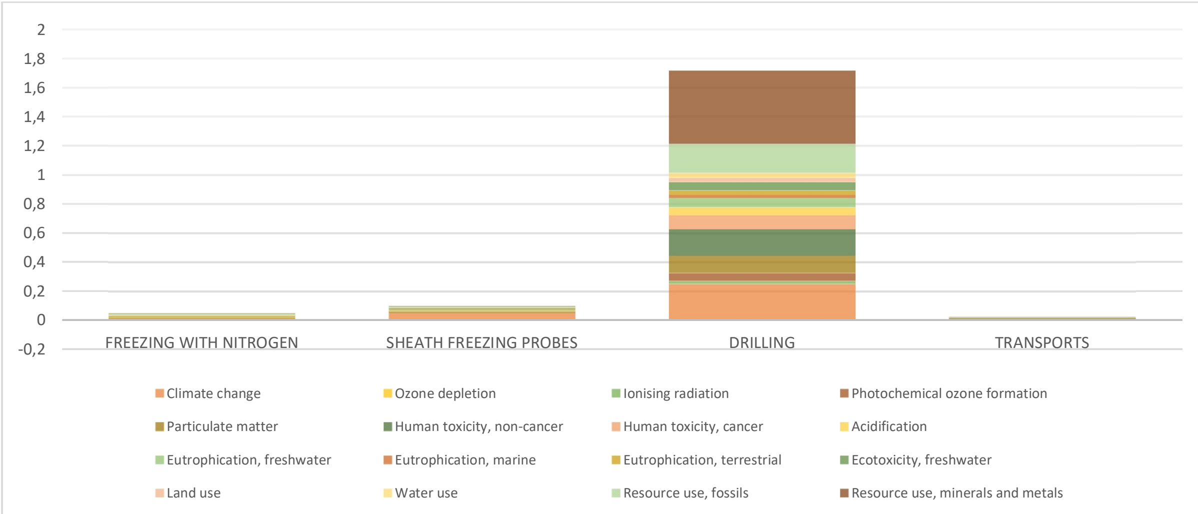


Fig. 8-36, Artificial ground freezing with nitrogen technique: impact, single point view.

Due to the fact that in the indirect method the refrigerant fluid comes to the working site already in the firm of liquid nitrogen, the steel piping plays a major role in site impact definition, with a 91.4% percentage.

Impact category	Unit	Total	FREEZING WITH NITROGEN	SHEATH	DRILLING	TRANSPORTATION
Total	%	100,0	2,5	5,1	91,4	1,0
Climate change	%	16,7	0,6	2,6	13,2	0,4
Ozone depletion	%	0,1	0,0	0,0	0,1	0,0
Ionising radiation	%	1,3	0,1	0,1	1,1	0,0
Photochemical ozone formation	%	3,2	0,1	0,2	2,9	0,1
Particulate matter	%	6,7	0,0	0,2	6,3	0,1
Human toxicity, non-cancer	%	9,8	0,0	0,1	9,7	0,0
Human toxicity, cancer	%	5,1	0,0	0,0	5,1	0,0
Acidification	%	3,4	0,1	0,3	3,0	0,1
Eutrophication, freshwater	%	4,1	0,4	0,3	3,4	0,0
Eutrophication, marine	%	1,3	0,0	0,1	1,1	0,0
Eutrophication, terrestrial	%	1,9	0,0	0,2	1,6	0,0
Ecotoxicity, freshwater	%	3,5	0,1	0,3	3,1	0,0
Land use	%	1,7	0,0	0,1	1,6	0,0
Water use	%	2,3	0,3	0,2	1,8	0,0
Resource use, fossils	%	12,0	0,6	0,5	10,6	0,3
Resource use, minerals and metals	%	27,0	0,0	0,0	26,9	0,0

Tab. 8-26, Artificial ground freezing with nitrogen technique: impact percentages, single point view.

The following table presents the results obtained during the characterisation phase, which will serve as a foundation for evaluating the Envision/DNSH indicators' framework.

Impact category	Unit	Total	NITROGEN FREEZING	SHEATH	DRILLING AND PIPES	MATERIAL AND EQUIPMENT TRANSPORTATION
Climate change	kg CO2 eq	12081,53160	414,17318	1877,24328	9522,97077	267,14437
Ozone depletion	kg CFC11 eq	0,00165	0,00004	0,00007	0,00148	0,00006
Ionising radiation	kBq U-235 eq	2020,55653	231,73892	82,07438	1690,12732	16,61591
Photochemical ozone formation	kg NMVOC eq	50,96231	0,93305	3,47337	45,68437	0,87152
Particulate matter	disease inc.	0,00084	0,00001	0,00002	0,00079	0,00002
Human toxicity, non-cancer	CTUh	0,00229	0,00000	0,00001	0,00227	0,00000
Human toxicity, cancer	CTUh	0,00008	0,00000	0,00000	0,00008	0,00000
Acidification	mol H+ eq	57,45410	2,24961	4,57310	49,72320	0,90819
Eutrophication, freshwater	kg P eq	4,46386	0,41153	0,37514	3,67545	0,00174
Eutrophication, marine	kg N eq	16,08678	0,40070	1,34576	14,04999	0,29033
Eutrophication, terrestrial	mol N eq	167,50348	3,50403	14,25496	146,55066	3,19384
Ecotoxicity, freshwater	CTUe	145972,33367	4376,15980	11109,02560	128983,86695	1503,28132
Land use	Pt	322307,70154	5799,40722	14607,63264	301811,07803	89,58365
Water use	m3 depriv.	5710,29778	756,07622	422,13063	4532,60164	-0,51071
Resource use, fossils	MJ	175307,43707	8708,35920	8045,79110	154838,02873	3715,25804
Resource use, minerals and metals	kg Sb eq	0,42718	0,00076	0,00070	0,42569	0,00003
Climate change - Fossil	kg CO2 eq	12045,89053	412,01281	1873,18138	9493,56789	267,12845
Climate change - Biogenic	kg CO2 eq	23,22929	1,05483	2,63457	19,52667	0,01322
Climate change - Land use and LU change	kg CO2 eq	12,41178	1,10554	1,42734	9,87620	0,00270

Tab. 8-27, Artificial ground freezing with nitrogen technique: impact percentages, characterization.

8.10.3 Nitrogen freezing LCA sensitivity analysis

The requirements/suggestions coming from the qualitative assessment with Envision (i.e. the main leverages to focus on) are:

- Energy: Improve consumption (a) reducing power production from diesel engines, (b) using electricity coming from providers that use a mix of production that includes renewable sources.
- Transportation: Improving the rating of diesel transportation fueled trucks.
- Cement: reduce the content in clinker (through pozzolana or fly ash additions).

To the aim of including these sustainability upgrades with respect to the original LCA baseline just described in detail, another sensitivity run of the LCA model has been performed with these modifications:

- Energy: use an energy mix 70% fossil and 30% renewable (for instance hydro coming from run off river generation), through the Ecoinvent string: Electricity, high voltage {IT}| electricity production, hydro, run-of-river | APOS, U.
- Cement: use Pozzolana-based cement instead of Portland-based cement, through the Ecoinvent string: Cement, pozzolana and fly ash 11-35% {Europe without Switzerland}| market for cement, pozzolana and fly ash 11-35% | APOS, U.
- Steel: use iron coming from scrap, through the Ecoinvent string Iron scrap, unsorted {RoW}| steel production, electric, low-alloyed | APOS, U.

- Transportation: use trucks Euro6 instead of Euro5, through the Ecoinvent string: Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U.

The analysis presented here should be considered as indicative due to the inherent limitations of using generic data from the Ecoinvent database. However, further improvements can be achieved by utilizing customized Environmental Product Declarations (EPDs) or conducting material-oriented Life Cycle Assessments (LCAs) provided by suppliers. Despite these limitations, the sensitivity calculation performed in this study provides a valuable insight into the potential enhancements in sustainability performance that could be achieved by incorporating the recommendations suggested by the Envision indicators.

Impact category	Unit	Total	NITROGEN FREEZING	SHEATH	DRILLING AND PIPES	MATERIAL AND EQUIPMENT TRANSPORTATION
Climate change	kg CO2 eq	10061,02892	414,17319	1531,07391	7931,48909	184,29274
Ozone depletion	kg CFC11 eq	0,00139	0,00004	0,00006	0,00125	0,00004
Ionising radiation	kBq U-235 eq	1323,91889	231,73893	69,00812	1011,51461	11,65723
Photochemical ozone formation	kg NMVOC eq	42,47470	0,93305	2,86763	38,43457	0,23946
Particulate matter	disease inc.	0,00057	0,00001	0,00002	0,00054	0,00001
Human toxicity, non-cancer	CTUh	0,00079	0,00000	0,00001	0,00077	0,00000
Human toxicity, cancer	CTUh	0,00003	0,00000	0,00000	0,00003	0,00000
Acidification	mol H+ eq	46,15744	2,24961	3,75981	39,78114	0,36688
Eutrophication, freshwater	kg P eq	3,14901	0,41153	0,34238	2,39377	0,00134
Eutrophication, marine	kg N eq	13,52445	0,40070	1,12527	11,93737	0,06112
Eutrophication, terrestrial	mol N eq	139,29496	3,50403	11,74604	123,36525	0,67965
Ecotoxicity, freshwater	CTUe	117535,74881	4376,15989	8933,40069	103164,28109	1061,90714
Land use	Pt	284353,19987	5799,40732	11757,37465	266731,28950	65,12839
Water use	m3 depriv.	4019,49971	756,07622	390,85179	2872,87745	-0,30575
Resource use, fossils	MJ	140064,39038	8708,35941	6681,00975	122064,90545	2610,11576
Resource use, minerals and metals	kg Sb eq	0,35424	0,00076	0,00063	0,35283	0,00002
Climate change - Fossil	kg CO2 eq	10033,76532	412,01282	1527,76029	7909,71079	184,28142
Climate change - Biogenic	kg CO2 eq	17,26840	1,05483	2,14791	14,05626	0,00940
Climate change - Land use and LU change	kg CO2 eq	9,99520	1,10554	1,16570	7,72204	0,00192

Tab. 8-28, Artificial ground freezing with nitrogen technique: sensitivity analysis based on materials, energy and transportation optimizations, impact indicators, characterization.

The subsequent table presents the synthesis of the performance outcomes for both the baseline and sensitivity analyses.

Material/ Consumption	Quantity	Unit
Cement	2111	kg
Energy-Electricity	61,6	kWh
Energy-Diesel	3240	kWh
Steel	3001	kg
T.A.M.	0	kg
Bentonite	192	kg
Nitrogen	1778,1	kg
Nitrogen waste	1778,1	kg
Brine waste	0	kg
Sludge waste	0	m3
Water	4094	kg

Impact category	Weighted single score	Total Sensitivity	Total Baseline	Unit	S/B
Climate change	18,91%	10061,02893	12081,53160	kg CO2 eq	-16,72%
Ozone depletion	0,00%	0,00139	0,00165	kg CFC11 eq	-15,86%
Ionising radiation	0,00%	1323,91889	2020,55653	kBq U-235 eq	-34,48%
Photochemical ozone formation	0,00%	42,47470	50,96231	kg NMVOC eq	-16,65%
Particulate matter	6,24%	0,00057	0,00084	disease inc.	-31,59%
Human toxicity, non-cancer	4,57%	0,00079	0,00229	CTUh	-65,58%
Human toxicity, cancer	0,00%	0,00003	0,00008	CTUh	-58,58%
Acidification	0,00%	46,15744	57,45410	mol H+ eq	-19,66%
Eutrophication, freshwater	0,00%	3,14901	4,46386	kg P eq	-29,46%
Eutrophication, marine	0,00%	13,52445	16,08678	kg N eq	-15,93%
Eutrophication, terrestrial	0,00%	139,29496	167,50348	mol N eq	-16,84%
Ecotoxicity, freshwater	0,00%	117535,74884	145972,33367	CTUe	-19,48%
Land use	0,00%	284353,19957	322307,70154	Pt	-11,78%
Water use	0,00%	4019,49973	5710,29778	m3 depriv.	-29,61%
Resource use, fossils	12,95%	140064,39123	175307,43707	MJ	-20,10%
Resource use, minerals and metals	30,36%	0,35424	0,42718	kg Sb eq	-17,07%

Tab. 8-29, Artificial ground freezing with nitrogen technique: sensitivity analysis vs. baseline, total impact indicators, characterization.

8.11 Comparison of the treatments' performances

The LCA assessments provide an environmental assessment of each approach and the comparative performance, from the perspective of several environmental effect categories, of each type of treatment

The representation of the data is conducted based on the baseline analysis as a point of reference.

The first graph illustrates the comparison of impact performance within each category of the Environmental Footprint Framework. Jet grouting techniques are of significant importance in all areas of impact, whilst the remaining three techniques contribute to various effect categories; remarkable the energy consumption influence for the freezing technlogy.

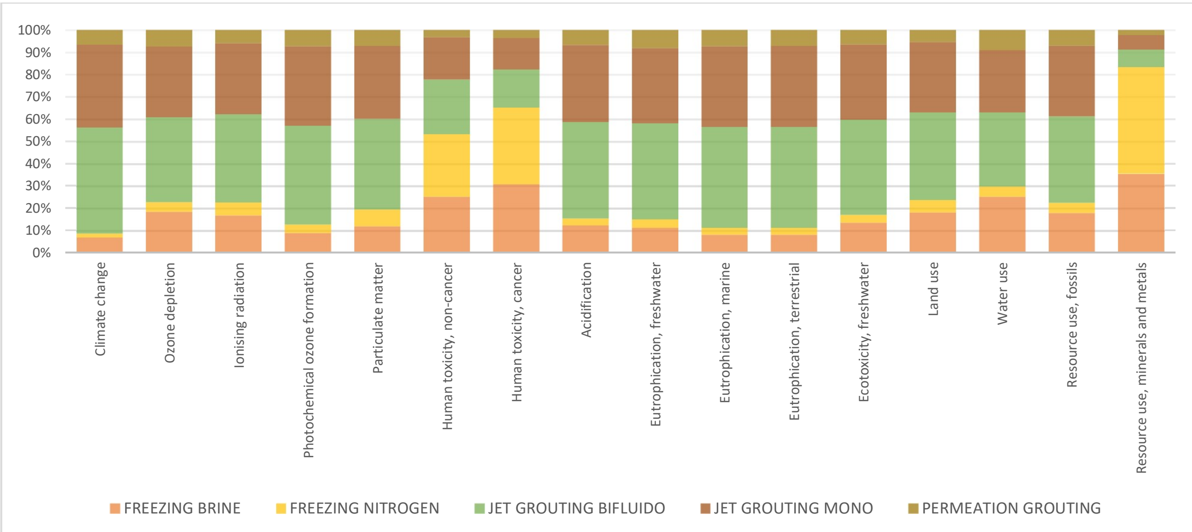


Fig. 8-37, Case studies techniques comparison: impact, characterization view.

In the subsequent normalized diagram, gives more evidence to what stated above Jet grouting techniques dominate impact for climate change, and those typical of the concrete industry.

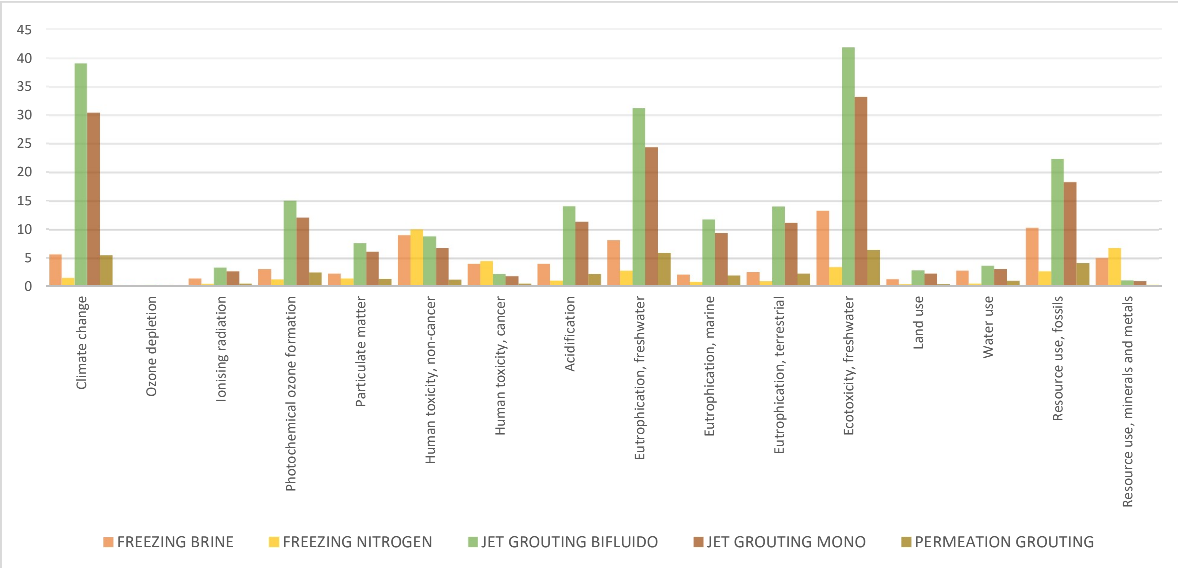


Fig. 8-38, Case studies techniques comparison: impact, normalized view.

The weighted view confirms the conclusions that have been drawn from the normalized view.

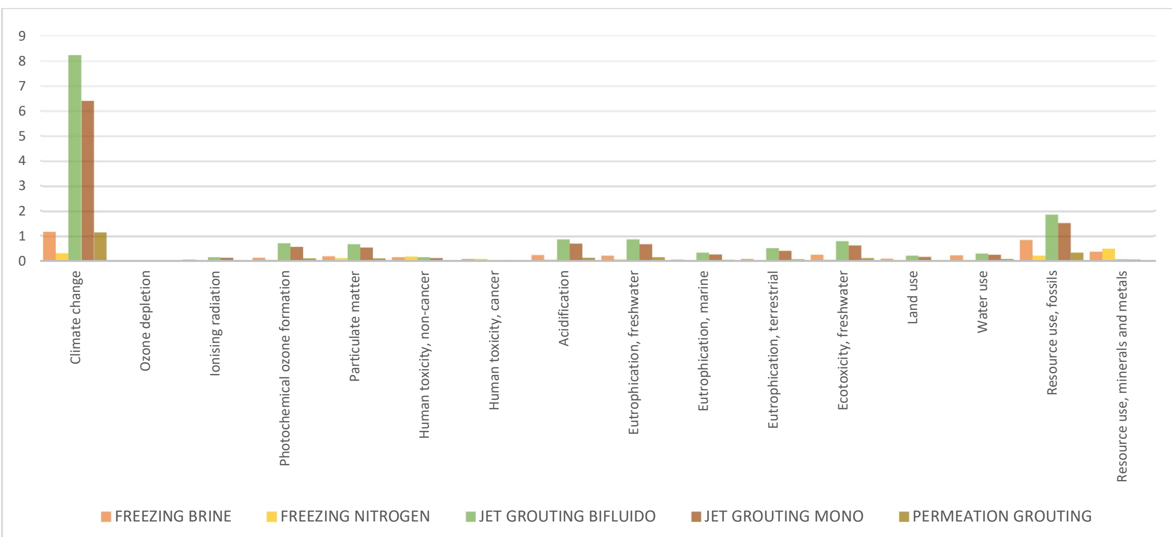


Fig. 8-39, Case studies techniques comparison: impact, weighted view.

The use of a single point representation now allows for a comprehensive assessment of the environmental efficacy exhibited by the five different treatment approaches. The performance disparities across technologies may be attributed to several factors such as climate change-induced impacts, resource depletion, air quality and human toxicity, and water consumption and depletion. This perspective allows for a quantitative assessment of these causes and presents relevant opportunities for potential enhancements.

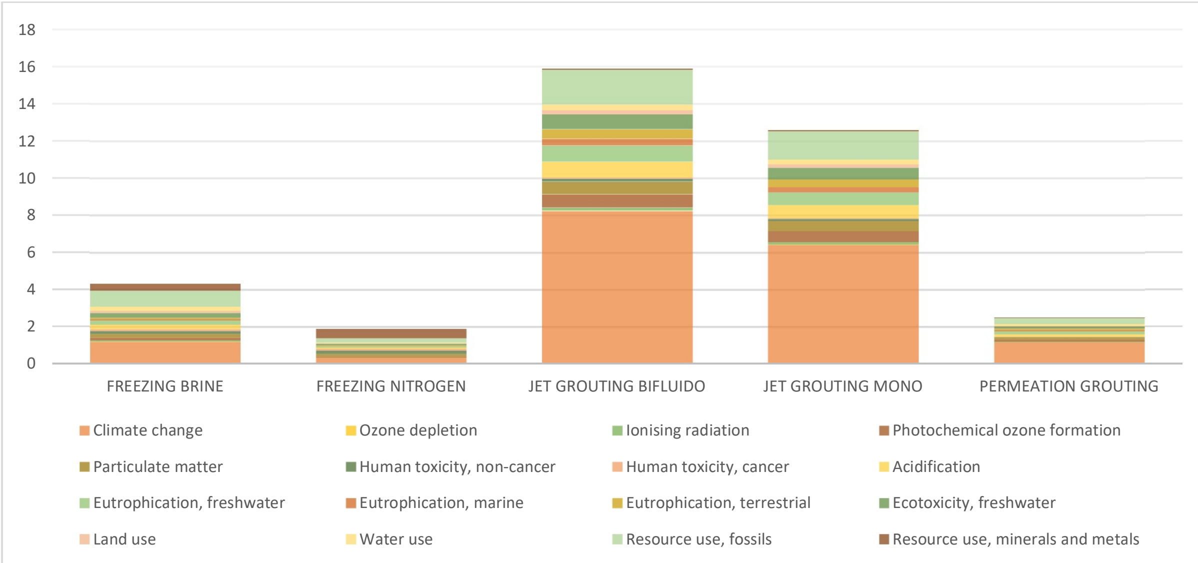


Fig. 8-40, Case studies techniques comparison: impact, single point/score view.

By comparing the total scores of the five case studies, it emerges that the nitrogen-freezing process is the one that impacts the less. This is mainly due to the role played by climate change, resource depletion, and water impacts induced by cement production and use. The grout effect in permeation grouting is compensated (when compared to brine freezing) by the material and energy relevance of the 'freezing' effort needed to keep brine in circulation. Finally, jet grouting, representing a solid and effective treatment, pays a high sustainability penalty due to the significant need for energy and grout cement-based mix.

The following table allows for the comparison between the different techniques: the heat map highlights (in red) the highest values for the quantitative KPIs of each impact category and confirms the above evaluations.

Impact category	Unit	PERMEATION GROUTING	JET GROUTING SINGLE FLUID	JET GROUTING DOUBLE FLUID	FREEZING BRINE	FREEZING NITROGEN
Climate change	kg CO2 eq	44162,18116	246215,44830	316196,39990	45377,18269	12081,53161
Ozone depletion	kg CFC11 eq	0,00279	0,01183	0,01422	0,00685	0,00165
Ionising radiation	kBq U-235 eq	2115,31387	11200,80211	13923,23464	5918,79626	2020,55654
Photochemical ozone formation	kg NMVOC eq	100,18710	488,39035	608,09381	122,45663	50,96231
Particulate matter	disease inc.	0,00080	0,00364	0,00452	0,00133	0,00084
Human toxicity, non-cancer	CTUh	0,00027	0,00155	0,00201	0,00206	0,00229
Human toxicity, cancer	CTUh	0,00001	0,00003	0,00004	0,00007	0,00008
Acidification	mol H+ eq	122,69145	627,28454	781,53838	221,86829	57,45410
Eutrophication, freshwater	kg P eq	9,42141	39,20071	50,10546	12,98632	4,46386
Eutrophication, marine	kg N eq	37,41535	182,96914	229,02614	41,12721	16,08678
Eutrophication, terrestrial	mol N eq	393,50655	1976,13326	2471,45650	443,28549	167,50348
Ecotoxicity, freshwater	CTUe	273202,00878	1417097,26782	1786505,06989	567979,18605	145972,33367
Land use	Pt	323969,19188	1864116,81548	2318539,97682	1073906,92763	322307,70222
Water use	m3 depriv.	11477,57963	35047,85458	41721,04968	31698,83055	5710,29780
Resource use, fossils	MJ	264587,27406	1189666,35757	1452697,14610	667564,16087	175307,43694
Resource use, minerals and metals	kg Sb eq	0,02053	0,05804	0,06998	0,31618	0,42718
Climate change - Fossil	kg CO2 eq	44070,27949	245697,90639	315550,19110	45124,85995	12045,89053
Climate change - Biogenic	kg CO2 eq	60,92449	337,16252	413,95098	209,80594	23,22929
Climate change - Land use and LU change	kg CO2 eq	30,97718	180,37939	232,25781	42,51680	12,41178

Tab. 8-30, Case studies techniques comparison: impact, characterization values.

9 The third phase of the assessment method: the framework scoring refinement

With the quantitative data developed in the previous chapter, the third step of the proposed three-phased method can be performed. The score evaluation of each sustainability indicator (within the framework Envision/DNSH) is assessed and discussed.

9.1 Permeation grouting assessment refinement

This is the closing phase, where the aim is to put all the contributions together and review the Envision framework results. The following table summarized the results of the LCA baseline and sensitivity runs. The major material and energy flows are also reported.

Material/ Consumption	Quantity	Unit
Cement	42751	kg
Energy-Electricity	2995	kWh
Energy-Diesel	3200	kWh
Steel	0	kg
T.A.M.	320	kg
Sludge waste	6.36	m3
Water	105900	kg

	Weighted single score	Total Sensitivity	Total Baseline	Unit	S/B
Climate change	44,89%	36927,3063	44162,18116	kg CO2 eq	-16,38%
Ozone depletion	0,00%	0,00251736	0,002792854	kg CFC11 eq	-9,86%
Ionising radiation	0,00%	1824,891663	2115,313875	kBq U-235 eq	-13,73%
Photochemical ozone formation	4,77%	86,75967776	100,1871036	kg NMVOC eq	-13,40%
Particulate matter	5,03%	0,000714601	0,000796777	disease inc.	-10,31%
Human toxicity, non-cancer	0,00%	0,000229547	0,000273693	CTUh	-16,13%
Human toxicity, cancer	0,00%	7,50983E-06	8,23528E-06	CTUh	-8,81%
Acidification	5,46%	104,6875206	122,6914512	mol H+ eq	-14,67%
Eutrophication, freshwater	7,09%	8,701845279	9,421410615	kg P eq	-7,64%
Eutrophication, marine	0,00%	32,5224058	37,41534811	kg N eq	-13,08%
Eutrophication, terrestrial	0,00%	338,0142282	393,5065501	mol N eq	-14,10%
Ecotoxicity, freshwater	4,76%	226507,5325	273202,0088	CTUe	-17,09%
Land use	0,00%	261138,5881	323969,1919	Pt	-19,39%
Water use	0,00%	10677,62947	11477,57963	m3 depriv.	-6,97%
Resource use, fossils	13,99%	233873,1103	264587,2741	MJ	-11,61%
Resource use, minerals and metals	*0,00%*	*0,018859693*	*0,020534279*	*kg Sb eq*	*-8,16%*

Tab. 9-1, Permeation grouting technique: quantities, energy consumptions and LCA results at a glance (single point cutoff below 4%) and sensitivity.

9.1.1 Permeation grouting assessment refinement based on the LCA analyses performed

This is the assessment of the evaluations of phase one.

- ***LD3.3 Conduct a Life-Cycle Economic Evaluation (estimated 50%).***
  - An economic evaluation of the five techniques is performed in a later chapter and is used to to compare and assess alternatives for at least one major design component. The requirement is fulfilled.
- ***RA1.1 Support Sustainable Procurement Practices (estimated 100%).***
  - Thanks to the analysis performed, it is possible to identify the environmental performance of each of the project materials, supplies, equipment and check whether they meet the sustainable procurement policy/program requirements. There are two levels of impact to be taken into account: (a) the relevance of the project in itself from gate to site, where the machinery on site is responsible for a 13.6% of impact (with 4.4% belonging to climate change, 3.3% to fossil resource use and 1.5% to particulate matter) and (b) the level of the products (cement mainly) that account for a 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 for

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 is confirmed.

- ***RA1.2 Use Recycled Materials (estimated 56%).***
  - To be able 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 again cement and grout in general. A concrete with recycled aggregates should be procured (for example using aggregates coming from recycling processes like steel mills secondary products, aggregated coming from demolition of concrete items, etc.). Another option is given by TAMs that can be made of recycled steel or plastics. Provided that these options are implemented, the score can be confirmed.
- ***RA2.2 Reduce Construction Energy Consumption (estimated 67%).***
  - To reach the target of requiring/implementing at least four (4) energy reduction strategies, these are the design choices that can be made: chose cement coming from a green supply chain, use truck EURO6 or more, use machinery for mixing powered by electricity, chose recycled aggregates for concrete. The score is confirmed.
- ***RA2.3 Use Renewable Energy (estimated 63%).***
  - To ensure that the project meets 50% of energy needs (electricity and fuel) from renewable sources, there are three possibilities: (a) cement comes from a supply chain that uses renewable energy or low content of clinker, (b) the sitework uses electric power and choses 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.
- ***CR1.1 Reduce Net Embodied Carbon (estimated 75%).***
  - The requirement here is that the project team demonstrates at least a 30% reduction in total embodied carbon of materials over the life of the project 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, nevertheless the assessment performed considering cement with less clinker, energy coming from renewable sources shows a benefit of no more than 16% in COeeq reduction. For this reason the score is downgraded to 10 (50%). More could be done with deeper/better information about the real case.
- ***CR1.2 Reduce Greenhouse Gas Emissions (estimated 69%).***
  - To reach the score, the project team must demonstrate at least a 25% reduction in total CO_2e over the operational life of the project compared to the baseline, and the project team has to map and calculate the total annual greenhouse gas emissions of the final project design for reporting purposes. The LCA calculation could provide this information because of the use of green cements and aggregates. The impact of cement on climate change using 'green' cement should be reduced significantly, still the quantification of this reduction is difficult to do. This team is carrying on further analyses [Associazione Infrastrutture Sostenibili, 2023] in order to catch the needed information from EPD declaration of cement and concrete producers. This means that, to date, the project does not allow for such a reduction and the score needs to be reduced. To the same conclusion comes the assessment evaluation mentioned before, that points to 16% CO_2eq reduction. Scaling back one step means that this goes to 8 and the percentage to 31%.
- ***LD1.4 Pursue Byproduct Synergies (estimated 33%).***
  - This indicator requires that 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. 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 coming 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 reused as construction filling material. The score is confirmed, because analysis has been performed and at least one byproduct is identified and used.

- ***RA1.4 Reduce Construction Waste (estimated 44%).***
  - In this case, the project team has to set a target goal for construction waste diversion: during construction at least 50% of waste materials are recycled, reused, and/or salvaged. Diversion may be a combination of waste-reduction measures and sourcing waste to other facilities for recycling or reuse. As said for the previous indicator, the main waste product is sludge, and collection and recycling is possible. It has also to be considered that TAM in themselves will stay in the ground after the injection; if self-degrading bio plastics is used (see for instance SIREG Durvinil Biosystem, where a high rate of biodegradation is expected), this can be considered as a waste reduction measure and the score can be confirmed.
- ***RA3.3 Reduce Construction Water Consumption (estimated 38%).***
  - To provide for at least one potable water conservation strategy to be implemented the use of grey water should be required during the mixing and the injection phases.

As a conclusion of this assessment conducted after the LCA analysis, only two scores had to be revised (CR.1.2 and CR.1.2)) and the overall scoring goes to 94/232 (41%), that still ranges high (gold rating).

9.1.2 Envision vs DNSH final ratings for the permeation grouting case.

Following the previous discussions on the relationship between the Envision indicators and the DNSH criteria requirements, we created a conceptual framework for ground improvement techniques that's creates a correspondence between the indicators and the requirements. Based on this approach, we associated the rating score proposed by Envision to the DNSH requirements. This provides a 'quantitative' and 'numerical' evaluation of the DNSH requirements.

Based on these premises, the following table summarizes and compares the results obtained after the refinement of the permeation grouting assessment. In order to provide a synthetic view , the Envision indicators have been grouped following the five main categories. The maximum scoring achievable for Envision is, as said, 232, and the corresponding maximum achievable with DNSH is 348. The performance of the permeation grouting technique is 41% for Envision and 43% for DNSH. Considering that this is obtained through provisions that exceed the baseline of the existing regulations, the evaluation is positive and landed on a 'gold' rating for Envision.

ENVISION Indicators by Category	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 resources OBJ 3	Circular economy transition OBJ 4	Pollution prevention OBJ 5	Biodoversity and ecosystem protection OBJ 6
Quality of Life	20	2	2	10%	0	0	0	0	0	0
Leadership	32	8	13	41%	0	0	0	6	6	0
Resource Allocation	88	18	54	61%	39	0	3	28	12	12
Natural World	28	5	5	18%	3	0	2	0	5	5
Climate and Resilience	64	10	20	31%	18	0	0	10	2	0
Envision	232	43	94	41%	60	0	5	44	25	17
DNSH	348	68	151	43%						

Tab. 9-2, Permeation grouting technique: Envision vs. DNSH revised ratings.

9.2 Single fluid jet grouting assessment refinement

Again, thanks to the LCA just presented in the previous chapter (the baseline and the sensitivity), an assessment of each of the more relevant scores is done and design/construction strategies for a better performance can be identified, in order to refine the design strategy to make it more sustainable. The following table summarizes the main data and compares the performances (in terms of the quantities coming from the life cycle assessment) of the baseline and the sensitivity. The main energy and material flows are reported.

Material/ Consumption	Quantity	Unit
Cement	323000	kg
Energy-Electricity	16497	kWh
Energy-Diesel	2516	kWh
Steel	0	kg
T.A.M.	0	kg
Sludge waste	214	m3
Water	323000	kg

	Weighted single score	Total Sensitivity	Total Baseline	Unit	S/B
Climate change	0,00%	243865,88401	297937,36176	kg CO2 eq	-18,15%
Ozone depletion	0,00%	0,01146	0,01348	kg CFC11 eq	-15,02%
Ionising radiation	4,52%	10917,13489	13043,89158	kBq U-235 eq	-16,30%
Photochemical ozone formation	4,34%	474,33955	578,32742	kg NMVOC eq	-17,98%
Particulate matter	0,00%	0,00356	0,00419	disease inc.	-15,05%
Human toxicity, non-cancer	0,00%	0,00153	0,00187	CTUh	-17,81%
Human toxicity, cancer	5,50%	0,00003	0,00004	CTUh	-15,03%
Acidification	5,44%	609,58859	745,56100	mol H+ eq	-18,24%
Eutrophication, freshwater	0,00%	38,60662	43,87501	kg P eq	-12,01%
Eutrophication, marine	0,00%	177,78931	215,75604	kg N eq	-17,60%
Eutrophication, terrestrial	5,05%	1919,40385	2349,61079	mol N eq	-18,31%
Ecotoxicity, freshwater	0,00%	1388365,93687	1734046,34667	CTUe	-19,93%
Land use	0,00%	1809977,69765	2269326,77323	Pt	-20,24%
Water use	11,96%	33285,37621	38826,54247	m3 depriv.	-14,27%
Resource use, fossils	0,00%	1154790,30521	1379881,30282	MJ	-16,31%
Resource use, minerals and metals	0,00%	0,05613	0,06825	kg Sb eq	-17,76%

Tab. 9-3, Single fluid jet grouting technique, quantities, energy consumptions and LCA results at a glance (single point cutoff below 4%) and sensitivity.

9.2.1 Single fluid jet grouting assessment refinement based on the LCA analyses performed

The following indicator evaluations are reported.

- ***LD3.3 Conduct a Life-Cycle Economic Evaluation (estimated 50%).***
  - An economic evaluation of the five techniques is performed in a later chapter and is used to to compare and assess alternatives for at least one major design component. The requirement is fulfilled.
- ***RA1.1 Support Sustainable Procurement Practices (estimated 100%).***
  - The LCA analysis identifies environmental performance of each of the project materials, supplies, equipment and check whether they meet the sustainable procurement policy/program requirements. The analysis shows the impact roles also at the level of the grout mix preparation subphase. There are two levels of impact to be taken into account: (a) the relevance of the project in itself from gate to site, where the machinery on site is responsible for a 9.5% of impact (primarily driven by 3.2% belonging to climate change and 2.3% to fossil resource use) and (b) the level of the products (cement mainly) that account for a 90.5% (primarily driven by 50.9 % belonging to climate change, 12.1% to fossil resource use), while less is due to transportation (2.5% impact overall) and drilling (1.7% impact overall). Looking a bit deeper in the grout mix preparation phase, cement accounts for nearly 95% of the impact with little remaining to water on site and turbomixing. It is important to notice that cement hits the top of nearly all the critical impacts, and this tells us that this one is a top offender in the construction world. Particularly in this case, design should require for cement mixtures different than Portland (pozzolanic, fly ash based etc. or clinker production with reduced

energy consumption and larger amounts of recycled components) and for contractors that ensure transportation fed with biofuel or machinery operated with electric power. With respect to permeation grouting, the amount of cement used in jet grouting is far more intensive and about five times (more than 300tons) larger than the permeation case. In the end this increases the impactful consequences of this approach, but, 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 is confirmed.

- ***RA1.2 Use Recycled Materials (estimated 56%).***
  - To be able 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 again cement and grout (through aggregate) in general (taking into consideration the full cradle to gate perspective). Concrete with recycled aggregates should be procured (for example using aggregates coming from recycling processes like steel mills secondary products, aggregated coming from demolition of concrete items, etc.) and also by avoiding Portland cement (using pozzolanic or fly ash based cement: this alone can give a 10% recycled amount, the remaining 15% can be provided through aggregates, that make more than 50% of a concrete mix).
- ***RA2.3 Use Renewable Energy (estimated 63%).***
  - To ensure that the project meets 30% of energy needs (electricity and fuel) from renewable sources, there are three possibilities that account for about 10% each: (a) cement comes from a supply chain that uses renewable energy or low content of clinker (replaced by fly ash or pozzolana), (b) the sitework uses electric power and choses a provider for electricity that sources from renewable sources, (c) the transportation is fueled with biofuels. Provided that these options are implemented, the score can be confirmed. The sensitivity analysis has been performed with these assumtions.
- ***CR1.1 Reduce Net Embodied Carbon (estimated 50%).***
  - The requirement here is that the project team demonstrates at least a 15% reduction in total embodied carbon of materials over the life of the project compared to the baseline. In this case, again, cement and aggregates are the leverages. The sensitivity analysis gives a gain of more than 18% in terms of CO2eq mobilization. Provided that the options for concrete are implemented, the score can be confirmed.
- ***CR1.2 Reduce Greenhouse Gas Emissions (estimated 50%).***
  - To reach the score, the project team must demonstrate at least a 25% reduction in total CO2e over the operational life of the project compared to the baseline, and the project team has to map and calculate the total annual greenhouse gas emissions of the final project design for reporting purposes. The LCA calculation could provide this information because of the use of green cements and aggregates. The impact of cement on climate change using 'green' cement should be reduced significantly, still the quantification of this reduction is difficult to do. This team is carrying on further analyses [Associazione Infrastrutture Sostenibili, 2023] in order to catch the needed information from EPD declaration of cement and concrete producers. The sensitivity already presented for this case and synthetized in the previous table gives a reduction of about 18% in CO2eq, starting from the baseline. Scaling back one step means that this goes to 8 and the percentage to 31%.
- ***LD1.4 Pursue Byproduct Synergies (33%).***
  - This indicator requires that 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. 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 coming 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 reused as construction filling material. The score is confirmed, because analysis has been performed and at least one byproduct is identified and used.

- ***RA1.4 Reduce Construction Waste (25%).***
    - In this case, the project team has to set a target goal for construction waste diversion: during construction at least 25% of waste materials are recycled, reused, and/or salvaged. Diversion may be a combination of waste-reduction measures and sourcing waste to other facilities for recycling or reuse. As said, the main waste product is sludge, and collection and recycling is possible and another bold can be obtained using aggregates coming from industrial processes. The score can be confirmed.
- ***RA2.2 Reduce Construction Energy Consumption (33%).***
    - To reach the target of requiring/implementing at least four (4) energy reduction strategies, these are the design choices that can be made: chose cement coming from a green supply chain, use truck EURO6 or more, use machinery for mixing powered by electricity, chose recycled aggregates for concrete. The score is confirmed.
- ***NW3.5 Protect Soil Health (38%).***
    - After completion, the treated soil behaves as concrete and loses its properties becoming an active element of the infrastructure. When the collection and treatment of sludge is properly done and any spill is avoided, the soil in the surroundings of the excavation could keep its properties and nature. Provided that specific actions in the design are provided this score can be confirmed.

Compared to a maximum reachable of 232 points, this ground improvement process scored 85 points (which means an overall value of 37%), with a score reduction only for CR.1.2. This could be considered an acceptable scoring (rewardable with a 'silver' rating following Envision rating scale).

9.2.2 Envision vs DNSH final ratings for the single fluid jet grouting case.

The following table shows the matching between the Envision scoring and the DNSH criteria. It is interesting to notice that OBJ 1 (related to materials and cement use) and OBJ 3 (related to recycling and waste reuse potential) allow better ratings for this specific technology heavily based on cement and energy use.

ENVISION Indicators by Category	Maximum ENVISION Points Available	Minimum ENVISION Points Available	Score Single fluid Jet Grouting		Scored EU environmental targets 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	Biodoversity and ecosystem protection OBJ 6
Quality of Life	20	2	2	10%	0	0	0	0	0	0
Leadership	32	8	13	41%	0	0	0	6	6	0
Resource Allocation	88	18	45	51%	32	0	1	25	12	12
Natural World	28	5	5	18%	3	0	2	0	5	5
Climate and Resilience	64	10	20	31%	18	0	0	10	2	0
Envision	232	43	85	37%	53	0	3	41	25	17
DNSH	348	68	139	40%						

Tab. 9-4, Single fluid jet grouting technique: Envision vs. DNSH revised ratings.

9.3 Double fluid jet grouting assessment refinement

This technique is similar to the previous one but aims to reducing construction time and schedule by using a more powerful injection devices and larger material quantities. These characteristics are directly reflected in the LCA analysis performance and in the Envision ratings. In the following, we analyze each of the relevant Envision indicators listed in phase one.

The following table summarizes the main data in terms of quantities and KPI impact indicators (for both the baseline analysis and the sensitivity). Again, the main energy and material flows are reported.

Material/ Consumption	Quantity	Unit
Cement	425000	kg
Energy-Electricity	10998	kWh
Energy-Diesel	1050	kWh
Steel	0	kg
T.A.M.	0	kg
Sludge waste	283	m3
Water	425000	kg

	Weighted single score	Total Sensitivity	Total Baseline	Unit	S/B
Climate change	51,78%	317711,94034	384881,11064	kg CO2 eq	-17,45%
Ozone depletion	0,00%	0,01432	0,01649	kg CFC11 eq	-13,18%
Ionising radiation	0,00%	14234,40491	16427,32747	kBq U-235 eq	-13,35%
Photochemical ozone formation	4,33%	587,47960	727,82150	kg NMVOC eq	-19,28%
Particulate matter	4,13%	0,00438	0,00525	disease inc.	-16,66%
Human toxicity, non-cancer	0,00%	0,00202	0,00243	CTUh	-17,18%
Human toxicity, cancer	0,00%	0,00004	0,00004	CTUh	-17,39%
Acidification	5,43%	776,69851	940,28271	mol H+ eq	-17,40%
Eutrophication, freshwater	5,57%	51,01587	56,42727	kg P eq	-9,59%
Eutrophication, marine	0,00%	221,46489	272,64744	kg N eq	-18,77%
Eutrophication, terrestrial	0,00%	2388,48662	2968,13777	mol N eq	-19,53%
Ecotoxicity, freshwater	5,13%	1821227,77274	2211604,42657	CTUe	-17,65%
Land use	0,00%	2401473,86489	2867315,42743	Pt	-16,25%
Water use	0,00%	44459,07287	47202,39701	m3 depriv.	-5,81%
Resource use, fossils	11,85%	1477694,64211	1712391,06776	MJ	-13,71%
Resource use, minerals and metals	0,00%	0,07216	0,08396	kg Sb eq	-14,06%

Tab. 9-5, Double fluid jet grouting technique: quantities, energy consumptions and LCA results at a glance (single point cutoff below 4%) and sensitivity analysis.

9.3.1 Double fluid jet grouting assessment refinement based on the LCA analysis performed

The following indicator evaluations are reported.

- ***LD3.3 Conduct a Life-Cycle Economic Evaluation (50%).***
  - An economic evaluation of the five techniques is performed in a later chapter and is used to compare and assess alternatives for at least one major design component. The requirement is fulfilled.
- ***RA1.1 Support Sustainable Procurement Practices (100%).***
  - Due to the heavy cement consumption (420k kg, compared to 323k kg and 43k kg of the other cases considered so far) and to a similar increase in water use (425k l, 323k l, 106k l), the strategy about sustainability performance should focus in this case on cement and sludge management. To be able 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, a cement with less clinker and a concrete with recycled aggregates should be procured (for example using cement added with fly ash, pozzolana or similar binders and aggregates coming from recycling processes like steel mills secondary products, aggregated coming from demolition of concrete items, etc.). Provided that these options are implemented, the score can be confirmed.
- ***RA2.3 Use Renewable Energy (63%).***
  - Power use increases due to high injection pressures but overall decreases in this particular case, due to time optimization, major relevance has electricity consumption, compared to

diesel consumption. More in detail, 11k kWh are used (compared to 16.5k kWh of the single fluid case and less than 4k kWh for the permeation grouting case). To ensure that the project meets 50% of energy needs (electricity and fuel) from renewable sources, there are three possibilities: (a) cement comes from a supply chain that uses renewable energy or low content of clinker, (b) the sitework uses electric power (particularly for the injection phase) and choses a provider for electricity that has a 50% of renewable sources, (c) the transportation is fueled with biofuels (and biofuel should be used for the drilling phase where diesel engines are used). All these assumptions have been used in the sensitivity analysis. Provided that these options are implemented, the score can be confirmed.

- ***RA1.2 Use Recycled Materials (38%).***
  - To be able to reach at least 15% (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 again cement and grout (through aggregate) in general (taking into consideration the full cradle to gate perspective). Concrete with recycled aggregates should be procured (for example using aggregates coming from recycling processes like steel mills secondary products, aggregated coming from demolition of concrete items, etc.) and also by avoiding Portland cement (using pozzolanic or fly ash based cement: this alone can give a 10% recycled amount, the remaining 15% can be provided through aggregates, that make more than 50% of a concrete mix). The assumption about this credit is more restrictive with respect to the single fluid case (25% set as target) due to the increase in materials use.
- ***RA1.4 Reduce Construction Waste (25%).***
  - In this case, the project team has to set a target goal for construction waste diversion: during construction at least 25% of waste materials are recycled, reused, and/or salvaged. Diversion may be a combination of waste-reduction measures and sourcing waste to other facilities for recycling or reuse. As said, the main waste product is sludge, and collection and recycling is possible and another bold can be obtained using aggregates coming from industrial processes. It has to be noted that the amount of sludge is larger than the cases analyzed so far: 283 m3, with respect to 214 m3 for the single fluid technique and less than 6.5 for permeation grouting. The score can be confirmed, even if the treatment effort is higher than the other cases.
- ***NW3.5 Protect Soil Health (38%).***
  - After completion, the treated soil behaves as concrete and loses its properties becoming an active element of the infrastructure. When the collection and treatment of sludge is properly done and any spill is avoided, the soil in the surroundings of the excavation could keep its properties and nature. Provided that specific actions in the design are provided this score can be confirmed.
- ***CR1.1 Reduce Net Embodied Carbon (25%).***
  - The ambition about this target has been realistically set to 5% reduction. This makes sense considering that the amount of CO2eq is far larger than the other cases (316 ton CO2eq, compared to 246 tons CO2eq for the single fluid technique and 44 tons CO2eq for permeation grouting). In this case, again, cement and aggregates are the leverages. To this aim the sensitivity has been performed and because of the heavy involvement of cement with reduced content of clinker and electricity coming from renewable sources, the reduction of CO2e with respect to the baseline is around 17%. The score can be increased to 8 (31%).
- ***CR1.2 Reduce Greenhouse Gas Emissions (31%).***
  - To reach the score, the project team must demonstrate at least a 10% reduction in total CO2e over the operational life of the project compared to the baseline, and the project team has to map and calculate the total annual greenhouse gas emissions of the final project design for reporting purposes. The target was already scaled with respect to permeation grouting in order to consider the effects of the more impactful nature of this treatment. The LCA calculation

could provide this information because of the use of green cements and aggregates. The impact of cement on climate change using ‘green’ cement should be reduced significantly, still the quantification of this reduction is difficult to do. This team is carrying on further analyses [Associazione Infrastrutture Sostenibili, 2023] in order to catch the needed information from EPD declaration of cement and concrete producers. The sensitivity carried out using the data available in the Ecoinvent database, sets the optimization with respect to the baseline to about 17%. This confirms the score.

Compared to a maximum reachable of 232 points, this ground improvement process scored 76 points (which means an overall value of 33%). This could be considered a good scoring (rewardable with a ‘silver’ rating following Envision rating scale).

9.3.2 Envision vs DNSH final ratings for the double fluid jet grouting case.

The following table shows the matching between the Envision scoring and the DNSH criteria. As for the previous case, it is interesting to notice that OBJ 1 (related to materials and cement use) and OBJ 3 (related to recycling and waste reuse potential) allow better ratings for this specific technology heavily based on cement and energy use.

					Scored EU environmental targets Permeation Grouting					
ENVISION Indicators by Category	**Maximum ENVISION Points Available**	**Minimum ENVISION Points Available**	**Score Double fluid Jet 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**	**Biodoversity and ecosystem protection OBJ 6**
Quality of Life	20	2	2	10%	0	0	0	0	0	0
Leadership	32	8	10	31%	0	0	0	3	3	0
Resource Allocation	88	18	39	44%	26	0	1	22	12	12
Natural World	28	5	5	18%	3	0	2	0	5	5
Climate and Resilience	64	10	20	31%	18	0	0	10	2	0
Envision	232	43	76	33%	47	0	3	35	22	17
DNSH	348	68	124	36%						

Tab. 9-6, Double fluid jet grouting technique: Envision vs DNSH revised ratings.

9.4 Brine ground freezing assessment refinement

The previous three techniques had the 'grouting' approach in common: ground improvement was reached through the injection of a concrete matrix within the existing soil, in one case strengthening the existing and in the other two just displacing the existing soil.

The next two treatments act in a very different way. Through a network of pipes the existing soil (immersed in the water table) is frozen, and its mechanical properties increased temporary, as long as freezing lasts. We can distinguish between the first freezing phase (that requires more energy) and the second freezing phase (that keeps the freezing state going). As a first technique, the use of brine as freezing liquid is presented.

As can be seen at a glance from the table below, material is mainly brine and steel and power play a major role in this technique. The table also shows the outcomes and the comparison from the LCA analyses performed (baseline and sensitivity).

Material/ Consumption	Quantity	Unit
Cement	2111	kg
Energy-Electricity	78278,6	kWh
Energy-Diesel	3240	kWh
Steel	5830	kg
T.A.M.	0	kg
Bentonite	192	kg
Brine waste	4915	kg
Sludge waste	0	m3
Water	4094	0

	Weighted single score	Total Sensitivity	Total Baseline	Unit	S/B
Climate change	28,35%	33378,19348	45377,18315	kg CO2 eq	-26,44%
Ozone depletion	0,00%	0,00507	0,00685	kg CFC11 eq	-25,97%
Ionising radiation	0,00%	4048,45519	5918,79628	kBq U-235 eq	-31,60%
Photochemical ozone formation	0,00%	92,56538	122,45663	kg NMVOC eq	-24,41%
Particulate matter	4,60%	0,00094	0,00133	disease inc.	-29,61%
Human toxicity, non-cancer	0,00%	0,00077	0,00206	CTUh	-62,60%
Human toxicity, cancer	0,00%	0,00003	0,00007	CTUh	-56,26%
Acidification	5,88%	161,31599	221,86829	mol H+ eq	-27,29%
Eutrophication, freshwater	5,17%	9,08107	12,98632	kg P eq	-30,07%
Eutrophication, marine	0,00%	31,09725	41,12721	kg N eq	-24,39%
Eutrophication, terrestrial	0,00%	333,16396	443,28549	mol N eq	-24,84%
Ecotoxicity, freshwater	6,06%	412217,08182	567979,19438	CTUe	-27,42%
Land use	0,00%	785600,01874	1073906,93792	Pt	-26,85%
Water use	5,27%	21746,53226	31698,83098	m3 depriv.	-31,40%
Resource use, fossils	20,25%	484622,77241	667564,16608	MJ	-27,40%
Resource use, minerals and metals	9,56%	0,24683	0,31618	kg Sb eq	-21,93%

Tab. 9-7, Ground freezing with brine technique: quantities, energy consumptions and LCA results at a glance (single point cutoff below 4%) and sensitivity analysis.

9.4.1 Brine ground freezing assessment refinement based on the performed LCA analysis

The following indicator evaluations are reported.

- ***LD3.3 Conduct a Life-Cycle Economic Evaluation (50%).***
  - An economic evaluation of the five techniques is performed in a later chapter and is used to compare and assess alternatives for at least one major design component. The requirement is fulfilled.
- ***RA1.1 Support Sustainable Procurement Practices (100%).***
  - To be able to reach at least 50% (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, in this case, steel. Pipes produced with steel coming from recycling are easy to find and could reasonably fill the whole 100% of the supply, and the sensitivity analysis performed considered steel coming from scrap. The little amount of bentonite and concrete is not relevant to the scope (even if Pozzolana was modelled in the analysis), while the criticality

of brine is more about the way the resulting sludge is handled. Provided that these options are implemented, the score can be confirmed.

- ***RA2.3 Use Renewable Energy (63%).***
  - To ensure that the project meets 30% of energy needs (electricity and fuel) from renewable sources, there are three possibilities: (a) steel production comes from a supply chain that uses a renewable power mix, (b) the sitework uses electric power and choses a provider for electricity that has a relevant supply from renewable sources, (c) the drilling while placing the pipe network and transportation are fueled with biofuels. The analysis shows that with 30% of electricity coming from renewable sources, CO2eq goes from 45.4 CO2eq tons to 35.4 CO2eq tons, with a better performance of almost all the other impact indicators. Provided that these options are implemented, the score can be confirmed.
- ***RA1.4 Reduce Construction Waste (63%).***
  - In this case, the project team has to set a target goal for construction waste diversion: during construction at least 75% of waste materials are recycled, reused, and/or salvaged. Diversion may be a combination of waste-reduction measures and sourcing waste to other facilities for recycling or reuse. As said for the previous indicator, the main waste product is brine sludge, and collection and recycling is possible. To make the brine suitable for reuse, it is possible to treat it with resins that target the contaminant metals for removal without being exhausted by sodium, thereby removing the unwanted contaminants while preserving the salt concentration in the brine solution (as a potential reuse of it, solutions with a high concentration of salt are known to reduce thermal conductivity, so brine waste is often recycled and reused as a cooling agent for steel heat exchangers in many power plants). The score can be confirmed.
- ***RA2.2 Reduce Construction Energy Consumption (67%).***
  - To reach the target of requiring/implementing at least four (4) energy reduction strategies, these are the design choices that can be made: chose steel coming from a green supply chain (modelled in the sensitivity), use truck EURO6 or more (used in sensitivity), use machinery for mixing powered by electricity (also in the baseline). These assumptions have been implemented in the sensitivity analysis. The score is confirmed.
- ***RA3.3 Reduce Construction Water Consumption (63%).***
  - To provide for at least one potable water conservation strategy to be implemented the use of grey water (strategy one) should be required during the mixing and the injection phases. As an alternative/integrative strategy (the second and third one), potable water should be recovered and reused as 'grey' in the site after grout and brine sludge treatment. As a fourth strategy, stormwater can be collected, stored and use for cleaning purposes in the site. The use of brine freezing as a technique for ground improvement is in itself a water consumption reduction strategy (fifth). The score is confirmed.
- ***CR1.1 Reduce Net Embodied Carbon (75%).***
  - The requirement here is that the project team demonstrates at least a 30% reduction in total embodied carbon of materials over the life of the project compared to the baseline. In this case, acting on energy, materials and transportation allows for a 26% of CO2eq reduction with respect to the baseline. Considering that some more saving can be obtained fueling transportation with biofuels and improving the performance of the drilling activities (again fueled with diesel engines), the target could be reached.
- ***CR1.2 Reduce Greenhouse Gas Emissions (69%).***
  - To reach the score, the project team must demonstrate at least a 50% reduction in total CO2e over the operational life of the project compared to the baseline, and the project team has to map and calculate the total annual greenhouse gas emissions of the final project design for reporting purposes. As per the previous indicator, the level of CO2eq is reduced of about 26%

with respect to the baseline, for this reason the target cannot be reached. The score is downgraded to 13, 50% of the maximum achievable.

- ***LD1.4 Pursue Byproduct Synergies (33%).***
  - This indicator requires that 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. 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 waste produced is sludge coming from brine and 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 reused as construction filling material. The score is confirmed, because analysis has been performed and at least one byproduct is identified and used.
- ***RA1.2 Use Recycled Materials (38%).***
  - To be able 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 again cement and grout in general. Steel coming from scrap recycling, as said previously, can be used instead of the virgin one. Provided that these options are implemented, the score can be confirmed.
- ***NW3.5 Protect Soil Health (38%).***
  - The ground freezing technique is by definition less invasive than grouting injection and soil is completely restored after having been frozen. The score is confirmed.

Compared to a maximum reachable of 232 points, this ground improvement process scored 109 points (which means an overall value of 47%) with the downgrade of CR.1.2. This could be considered a good scoring (rewardable with a 'gold' rating following Envision rating scale).

9.4.2 Envision vs DNSH final ratings for the Brine freezing case.

Compared to the other techniques, the picture of ground freezing apparently looks similar, but the blend of the different contributions is decidedly different: materials are less involved, while the impact are provided mainly by energy consumption and nature.

The overall score achieved is better for both Envision and DNSH with respect to the grouting techniques.

					Scored EU environmental targets Permeation Grouting					
ENVISION Indicators by Category	**Maximum ENVISION Points Available**	**Minimum ENVISION Points Available**	**Score Brine Ground Freezing**		**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**	**Biodoversity and ecosystem protection OBJ 6**
Quality of Life	20	2	5	25%	0	0	0	0	0	0
Leadership	32	8	13	41%	0	0	0	6	6	0
Resource Allocation	88	18	56	64%	42	0	5	28	12	12
Natural World	28	5	5	18%	3	0	2	0	5	5
Climate and Resilience	64	10	30	47%	28	0	0	15	2	0
Envision	232	43	109	47%	73	0	7	49	25	17
DNSH	348	68	171	49%						

Tab. 9-8, Ground freezing with brine technique: Envision vs. DNSH revised ratings.

9.5 Nitrogen freezing ground assessment refinement

The nitrogen based freezing treatment is very similar to the brine type, with the exception for the fluid used that is liquid nitrogen (delivered already liquefied at the site). We can distinguish between the first freezing phase (that requires more energy) and the second freezing phase (that keeps the freezing state going). As a first technique, the use of brine as freezing liquid is presented.

As can be seen at a glance from the table below, material is mainly nitrogen and steel and power plays a minor role in this technique, with respect to the previous one. The table gives an overview of the differences between the baseline and the sensitivity LCA analyses performed. The main energy and material flows are given.

Material/ Consumption	Quantity	Unit
Cement	2111	kg
Energy-Electricity	61,6	kWh
Energy-Diesel	3240	kWh
Steel	3001	kg
T.A.M.	0	kg
Bentonite	192	kg
Nitrogen	1778,1	kg
Nitrogen waste	1778,1	kg
Brine waste	0	kg
Sludge waste	0	m3
Water	4094	kg

Impact category	Weighted single score	Total Sensitivity	Total Baseline	Unit	S/B
Climate change	18,91%	10061,02893	12081,53160	kg CO2 eq	-16,72%
Ozone depletion	0,00%	0,00139	0,00165	kg CFC11 eq	-15,86%
Ionising radiation	0,00%	1323,91889	2020,55653	kBq U-235 eq	-34,48%
Photochemical ozone formation	0,00%	42,47470	50,96231	kg NMVOC eq	-16,65%
Particulate matter	6,24%	0,00057	0,00084	disease inc.	-31,59%
Human toxicity, non-cancer	4,57%	0,00079	0,00229	CTUh	-65,58%
Human toxicity, cancer	0,00%	0,00003	0,00008	CTUh	-58,58%
Acidification	0,00%	46,15744	57,45410	mol H+ eq	-19,66%
Eutrophication, freshwater	0,00%	3,14901	4,46386	kg P eq	-29,46%
Eutrophication, marine	0,00%	13,52445	16,08678	kg N eq	-15,93%
Eutrophication, terrestrial	0,00%	139,29496	167,50348	mol N eq	-16,84%
Ecotoxicity, freshwater	0,00%	117535,74884	145972,33367	CTUe	-19,48%
Land use	0,00%	284353,19957	322307,70154	Pt	-11,78%
Water use	0,00%	4019,49973	5710,29778	m3 depriv.	-29,61%
Resource use, fossils	12,95%	140064,39123	175307,43707	MJ	-20,10%
Resource use, minerals and metals	30,36%	0,35424	0,42718	kg Sb eq	-17,07%

Tab. 9-9, Ground freezing with nitrogen technique: quantities, energy consumptions and LCA results at a glance (single point cutoff below 4%) and sensitivity analysis.

9.5.1 Nitrogen ground freezing assessment refinement based on the performed LCA analysis

The following indicator evaluations are reported.

- ***LD3.3 Conduct a Life-Cycle Economic Evaluation (50%).***
  - An economic evaluation of the five techniques is performed in a later chapter and is used to to compare and assess alternatives for at least one major design component. The requirement is fulfilled.
- ***RA1.1 Support Sustainable Procurement Practices (100%).***
  - To be able to reach at least 50% (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, in this case, steel. Pipes produced with steel coming from recycling are easy to find and could reasonably fill the whole 100% of the supply. The little amount of bentonite and concrete is not relevant to the scope, while the criticality of brine is more about the way the resulting sludge is handled. Provided that these options are implemented, the score can be confirmed.
- ***RA2.3 Use Renewable Energy (63%).***

- To ensure that the project meets 30% of energy needs (electricity and fuel) from renewable sources, there are three possibilities: (a) steel production comes from a supply chain that uses a renewable power mix, (b) the sitework uses electric power and choses a provider for electricity that has a relevant supply from renewable sources, (c) the drilling while placing the pipe network and transportation are fueled with biofuels. These strategies have been implemented in the sensitivity analyses. Provided that these options are implemented, the score can be confirmed.

- ***RA1.4 Reduce Construction Waste (63%).***
  - In this case, the project team has to set a target goal for construction waste diversion: during construction at least 75% of waste materials are recycled, reused, and/or salvaged. Diversion may be a combination of waste-reduction measures and sourcing waste to other facilities for recycling or reuse. As said for the previous indicator, the main waste product is sheath sludge, and collection and recycling is possible. The score can be confirmed.
- ***RA2.2 Reduce Construction Energy Consumption (67%).***
  - To reach the target of requiring/implementing at least four (4) energy reduction strategies, these are the design choices that can be made: chose steel coming from a green supply chain, use truck EURO6 or more, use machinery for mixing powered by electricity. These strategies have been implemented in the sensitivity analyses. The score is confirmed.
- ***RA3.3 Reduce Construction Water Consumption (63%).***
  - To provide for at least five potable water conservation strategy to be implemented the use of grey water (strategy one) should be required during the mixing and the injection phases. As an alternative/integrative strategy (the second one), potable water should be recovered and reused as ‘grey’ in the site after grout sludge treatment. As a third strategy, stormwater can be collected, stored and use for cleaning purposes in the site. The use of nitrogen freezing as a technique for ground improvement is in itself a water consumption reduction strategy (fourth). The technique does not allow for a fifth strategy. The score is downgraded to 3 (38%).
- ***CR1.1 Reduce Net Embodied Carbon (75%).***
  - The requirement here is that the project team demonstrates at least a 30% reduction in total embodied carbon of materials over the life of the project compared to the baseline. In this case, again, cement and aggregates are the leverages. Still, due to the nature of the technique, the main focus is energy and energy use. The sensitivity performed allows for no more that 16% CO_2eq reduction with respect to the baseline (including the use of iron coming from scrap). Therefore, the score has to be downgraded to 10 (50%).
- ***CR1.2 Reduce Greenhouse Gas Emissions (69%).***
  - To reach the score, the project team must demonstrate at least a 50% reduction in total CO_2e over the operational life of the project compared to the baseline, and the project team has to map and calculate the total annual greenhouse gas emissions of the final project design for reporting purposes. The LCA assessment provides an improvement of about 16% in kg CO_2eq with respect to the baseline. This means that, to date, the project does not allow for such a reduction and the score needs to be reduced. Scaling back one step means that this goes to 8 and the percentage to 31%.
- ***LD1.4 Pursue Byproduct Synergies (33%).***
  - This indicator requires that 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. 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 waste produced is sludge coming 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 reused as construction filling material. The score is confirmed, because analysis has been performed and at least one byproduct is identified and used.

- ***RA1.2 Use Recycled Materials (38%).***
    - To be able to reach at least 15% (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 again cement and grout in general. A concrete with recycled aggregates should be procured (for example using aggregates coming from recycling processes like steel mills secondary products, aggregated coming from demolition of concrete items, etc.). Again, renewables and biofuel could be a chance for improvement. The score can be confirmed.
- ***NW3.5 Protect Soil Health (38%).***
    - The ground freezing technique is by definition less invasive than grouting injection and soil is completely restored after having been frozen. The score is confirmed.

Compared to a maximum reachable of 232 points, this ground improvement process scored 101 points (which means an overall value of 44%), with the following actions against the scoring of the indicators: RA.2.2 increased while CR.1.2, CR.1.1, RA3.3 have been decreased. When confirmed by the analyses, this could be considered a good scoring (rewardable with a ‘gold’ rating following Envision rating scale).

9.5.2 Envision vs DNSH final ratings for the nitrogen freezing case.

Compared to the other techniques, the picture of ground freezing apparently looks similar, but the blend of the different contributions is decidedly different: materials are less involved, while the impact are provided mainly by energy consumption and kind.

The overall score achieved is better for both Envision and DNSH with respect to the grouting techniques.

ENVISION Indicators by Category	Maximum ENVISION Points Available	Minimum ENVISION Points Available	Score Nitrogen Ground Freezing		Scored EU environmental targets 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	Biodoversity and ecosystem protection OBJ 6
Quality of Life	20	2	5	25%	0	0	0	0	0	0
Leadership	32	8	13	41%	0	0	0	6	6	0
Resource Allocation	88	18	58	66%	37	0	3	28	12	12
Natural World	28	5	5	18%	3	0	2	0	5	5
Climate and Resilience	64	10	20	31%	18	0	0	10	2	0
Envision	232	43	101	44%	58	0	5	44	25	17
DNSH	348	68	149	43%						

Tab. 9-10, Ground freezing with nitrogen technique: Envision vs DNSH revised ratings.

9.6 Final view of the sustainability performance following Envision and DNSH

The following table summarizes the final evaluation with the Envision/DNSH framework, based on the LCA baseline and sensitivity runs.

	Maximum ENVISION Points Available	Minimum ENVISION Points Available	Score Permeation grouting		Score Single fluid Jet Grouting		Score Double fluid Jet Grouting		Score Brine Ground Freezing		Score Nitrogen Ground Freezing	
QL1.4	12	1	1	8%	1	8%	1	8%	3	25%	3	25%
QL1.6	8	1	1	13%	1	13%	1	13%	2	25%	2	25%
LD1.4	18	3	6	33%	6	33%	3	17%	6	33%	6	33%
LD3.3	14	5	7	50%	7	50%	7	50%	7	50%	7	50%
RA1.1	12	3	12	100%	12	100%	12	100%	12	100%	12	100%
RA1.2	16	4	9	56%	9	56%	6	38%	6	38%	6	38%
RA1.4	16	4	7	44%	4	25%	4	25%	10	63%	10	63%
RA2.2	12	1	8	67%	4	33%	1	8%	8	67%	12	100%
RA2.3	24	5	15	63%	15	63%	15	63%	15	63%	15	63%
RA3.3	8	1	3	38%	1	13%	1	13%	5	63%	3	38%
NW2.4	20	2	2	10%	2	10%	2	10%	2	10%	2	10%
NW3.5	8	3	3	38%	3	38%	3	38%	3	38%	3	38%
CR1.1	20	5	10	50%	10	50%	10	50%	15	75%	10	50%
CR1.2	26	3	8	31%	8	31%	8	31%	13	50%	8	31%
CR1.3	18	2	2	11%	2	11%	2	11%	2	11%	2	11%
Envision	232	43	94	41%	85	37%	76	33%	109	47%	101	44%
DNSH	348	68	151	43%	139	40%	124	36%	171	49%	149	43%

Tab. 9-11, Case studies comparison, impact, characterization values.

10 Another facet part 1: Quantitative cost assessment through life cycle cost analysis

10.1 The cost perspective: Cradle to site LCCA of the case studies

An economic evaluation has been conducted on the five approaches, utilizing current market pricing in 2022 and considering the flow/materials outlined in the preceding chapters and employed in the life cycle evaluations.

Description	Unit	Cost	Permeaton grouting		Jet grouting mono fluid		Jet grouting double fluid		Freezing indirect system (Brine)		Freezing direct system (LN)	
			QT	Amount	QT	Amount	QT	Amount	QT	Amount	QT	Amount
TOTAL VALUE				122.265,60 €		223.139,76 €		281.276,00 €		604.752,44 €		586.500,00 €
Site preparation	forfait	1		35.000,00 €		45.000,00 €		48.000,00 €		200.000,00 €		
Steel pipes connection	m	100,00 €							180	18.000,00 €	135	13.500,00 €
Drilling	m	55,12 €	420	23.150,40 €	1010	55.671,20 €	420	23.150,40 €	420	23.150,40 €	420	23.150,40 €
Deviation	m	25,00 €							420	10.500,00 €	420	10.500,00 €
PVC pipe installation	m	22,79 €	436,8	9.954,67 €								
Freezing pipe installation	m	100,00 €							420	42.000,00 €	420	42.000,00 €
Plastic sheath	m	14,88 €	420	6.249,60 €					420	6.249,60 €	420	6.249,60 €
Cement	t	220,00 €	52	11.440,00 €	323,2	71.104,00 €	425	93.500,00 €				
Grouting	mc	239,15 €	152,5	36.470,93 €								
Jet grouting MF Ø1000*	m	132,47 €			808	51.364,56 €						
Jet grouting DF Ø1800*	m	416,00 €					336	116.625,60 €				
Freezing - Brine	d	5.700,00 €							30	171.000,00 €		
Maintenance - Brine	d	4.100,00 €							30	123.000,00 €		
Energy Freezing Brine	kWh	0,184 €							36800	6.780,47 €		
Energy Maintenance Brine	kWh	0,184 €							22100	4.071,97 €		
Freezing - LN	lt	0,15 €									864000	129.600,00 €
Maintenance - LN	lt	0,15 €									810000	121.500,00 €
Exercise - LN	d	8.000,00 €									30	240.000,00 €

Tab. 10-1, Cost estimation for the five techniques, focus on the construction processes.

The estimation is derived from the design assumptions of the ideal case study provided, current market prices, and the team's professional expertise in similar projects.

10.2 Life cycle cost analysis for the case studies

For the case of construction processes, which is the level of the LCA analysis considered in this thesis, the cost evaluation spans a length shorter than the entire life cycle. A whole life cycle cost assessment makes sense when a medium- to long-term operation perspective is taken for the infrastructure. In this sense, the proposed evaluation made here might be thought of as a “brick” to be inserted into the broader assessment framework: the cost of the particular geotechnical intervention provides valuable input in the overall assessment of the infrastructure.

Still, from the perspective of the construction process, the cost point of view is critical to the decision-makers. This is why the three-phased method evaluation should be made in conjunction with a complete cost analysis.

The soil treatment techniques that have been described, because of their technological nature, imply peculiarities that can have a significant weight in the sustainability framework under both the aspects of the costs and of the overall infrastructure conception.

At first, these techniques are often used for building temporary structures that end their functionality once the primary final structure has been completed and becomes able to carry autonomously the loads previously acting on the provisional treated soil structure. This is the case of our ideal case design study example, where the treatment 'prepares' the execution of a final lining made after the opening excavation.

For soil permeation and jet grouting, the treatment impact and its cost end when the intervention is completed: the functions of the side's mechanical retaining and hydraulic watertightness are then provided in a "passive" mode. Soil freezing treatment also includes the excavation stage, where it remains "active" to provide its static and hydraulic functionality fully.

A differentiation between these technologies shall come out also in a further stage of the LCA/LCCA, beyond the "gate", for example, in the decommissioning stage: grouting produces a physical, permanent change of the ground fabric (voids filling and grain cementation in permeation grouting; partial substitution and more homogeneous cementation up to produce a sort of poor concrete in jet grouting), while freezing freezes the groundwater temporarily. The latter technology may also produce different impacts, for instance, during the thawing phase: in cohesive soils (silt, clay) settlements quickly develop to the point that the design foresees an accurate monitoring system of soil and structures behavior and remediation intervention, such as compensation grouting, to be performed after the freezing work according to the ongoing controls.

The latter phenomena evidence the concept of uncertainty implied in assessing structures' behavior. For the geotechnical structures, we talk of "epistemic uncertainty", associated with the fact that the treatments concern the natural, existing soil, which actual conditions are just generally known and lack of knowledge about its state persists; their execution must be managed differently, for example, from the construction of a new structure made by concrete or steel, where an aleatory uncertainty is related to the randomness due to a specific operation (the cast of a beam) [Der Kiureghan, Ditlevsen - 2009; Spross et al. – 2022]. This concept has a direct impact on the LCA of soil treatments: as an effect of the actual soil conditions, performing them, the material consumption may vary more or less as compared to the design prediction made based on the preliminary geotechnical investigation [Purdy, 2022]. In the analyzed case study is the cement grout quantity for the permeation grouting and the jet grouting, as well as the liquid nitrogen or energy for the brine cooling and pumping plant consumption for the ground freezing. This variability, originated by the epistemic uncertainty, has been considered in the case study adopting consumption amounts derived from the practice, and it is reflected in the cost evaluation. Another similar example is given by the drilling deviation in the ground, which usually is considered as an aleatory uncertainty related to the drilling operation, but that, when performed in soil strata including cobblestones and boulders, could be more precisely defined affected by an epistemic uncertainty.

Going back to the soil treatment scope, in some cases, it has a permanent function, as, for example, in creating impervious curtains for dams or along riversides, in improving soil behavior against sand liquefaction, and in improving ground mechanical behavior for shallow foundation or micropiles (i.e. tubfix bulbs). It involves an impact on the LCA and LCCA beyond the "gate" stage because the efficiency of the so-created geotechnical structure has to be checked over time, according to the observational method, by monitoring one or more critical parameters, as well as it may require a maintenance intervention.

An example is an impervious curtain in the ground made with the permeation grouting technique. The efficiency check can occur by monitoring the groundwater level with piezometers over time. In case of anomalies, performing permeability tests in drilling holes may be possible. Finally, a "maintenance" intervention can be set up by performing new permeation grouting treatments in the missing zone of the curtain. A similar strategy shall be considered in the LCA and LCCA for a definitive intervention.

Consider also the treatment time execution: it impacts straightforwardly on the pilot case LCA. Nevertheless, it can fall into a broader framework of an infrastructure sustainability assessment, for example, by defining its construction stages. There may be conditions in which several soil treatments can or must be performed simultaneously, as well as, on the contrary, they have to be carried out at different moments, impacting the related costs.

Finally, there are conditions where an intervention may be partially exploited (and therefore re-used) for further building stages of a structure or infrastructure, with effects on the LCA and the LCCA of a single process and the overall work. Considering the pilot case, consider excavating a new opening beside the first one, exploiting the treatment made for one of its walls. The grouting treatments ("passive" type) could be directly re-used without any new intervention. Differently, the freezing treatments ("active" type) would require the re-activation of the cooling circuits, with a wide range of consumption (of nitrogen or energy), depending on this takes place a long time after the completion of the previous work, with the thawing of the soil, as well as just at the end of the same work, with the possibility even to go on with the maintenance stage of the already frozen soil wall.

So, considering the "cradle-to-gate" approach of the presented method, we provide in the following chapter a cost evaluation of each work made with the different analyzed technologies, referring to the pilot case, putting in evidence their necessary execution times up to the end of the lining cast, neglecting any impact produced on the excavated material.

10.3 Synthesis and comparison of the 5 cost impact analys

The cost of the different soil treatment solutions analyzed in the pilot case has been presented in the previous table of the chapter.

Permeation grouting results as the most cost-effective technology, followed by the jet grouting treatments while freezing treatments appear to be more expensive, around two times that the jet grouting works.

The following figure, based on the estimate above, gives the data by distinguishing the cost for the site preparation, the drilling and pipe installation (evaluable only for permeation grouting and ground freezing), and the typical activity of each technology: the injection for the permeation grouting, the jet grouting (including the drilling phase) and the freezing process with brine or LN. Also, the total treatment execution time is shown.

The costs of the site plants for the grouting-based technologies are similar and grow with the complexity of the equipment: low-pressure pumps for the permeation grouting, high-pressure pumps for single-fluid jet grouting, additional air compressors and larger grout mixers for double-fluid jet grouting.

The closed system freezing plant has a high-cost impact due to the complexity of the refrigerator group for the brine that requires a secondary plant with a cooling tower. On the contrary, in this case, the freezing open system is very cost-effective because it requires just the distribution plant to be fed directly by the truck that delivers the liquid nitrogen on-site. In a more complex context, it must be considered the presence of tanks for the storage of the cement for the grouts (permeation grouting and jet grouting) and of the liquid nitrogen, as well as an additional freezing group for the freezing brine system (usually together with a back-up group for guaranteeing the freezing process continuity also in case of breakdown of one unit).

The drilling activity is common to all the technologies, and its impact on the costs hangs on the necessary drilling total length, except for the freezing, which requires an additional cost for performing an exact survey of the drilling deviations necessary for the correct management of the treatment process; this is based on the interpretation of the temperature in the soil (given by thermometric sensors placed into dedicate additional pipes) at a known distance from the cooling source, i.e. the freezing pipes.

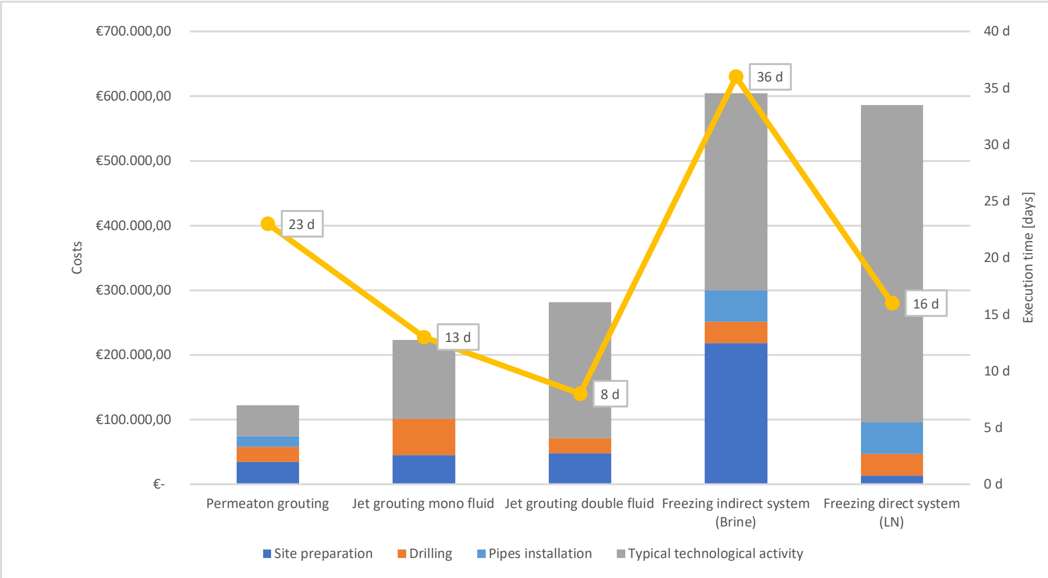


Fig. 10-1, Quantitative cost assessment of the different treatment solution analyzed with the pilot case – Main cost classes (For jet grouting cases, drilling is included in the typical technological activity

The pipe installation in the ground is necessary for the permeation grouting, where PVC pipes are used, and for the ground freezing, where special double coaxial stainless-steel pipes must be adopted. The cost difference between the two technologies comes from the different materials and constitutions.

The significant cost difference is then generally given by the typical material dosage for each technology. The volume quantity of cement grout injected with the permeation grouting (around 150 mc) is lower than with the jet grouting: around 430 mc with the simple fluid system and around 560 mc with the double fluid system. Technology complexity in the two latter systems impacts the execution cost voices. The freezing open system shows a very high cost due to the liquid nitrogen; this evidence the high importance of the process management using this technology, which, as seen from the LCA analysis, appears as the less impactful technology among the five considered in this analysis. The freezing closed system costs are related to the cost of managing and maintaining the brine freezing plant and distribution circuit, together with the electrical energy consumption.

The figure also plots the execution timing that has been estimated in labor days. They have been evaluated starting from drilling to when the treatment is effective, and the excavation can start.

For the jet grouting technologies, the high number of columns necessary for the treatment, deriving from their geometrical dimensions (Ø1,00 m for single fluid, Ø1,80 m for double fluid) impacts directly on the execution times. The permeation grouting appears as a slowly technology, but at the scale of the pilot case it is definitely underused: in facts a single plant can serve up to 15-20 grouting pumps, while for the studied case only 2 were necessary. The freezing times using liquid nitrogen vary usually between 7 and 12 days, being influenced more by the soil nature than from the soil volume to be treated. This is true also for the brine system, but in a range of time varying between 30 and 60 days. The short times of the open cycle system can be performed thanks to the particularly high cryogenic power provided by the liquid nitrogen technology, differently from the brine used in the closed cycle system.

The following table summarizes the cost and time data concerning the techniques together with the Envision/DNSH scoring.

CATEGORY	PERMEATION GROUTING	JET GROUTING SINGLE FLUID	JET GROUTING DOUBLE FLUID	BRINE FREEZING	NITROGEN FREEZING
Envision rating (% total score)	45%	39%	31%	49%	49%
DNSH rating (% total score)	48%	41%	33%	51%	48%
Project cost (€ 2020)	122265,6	223140	281276	604752	586500
Project duration (days)	23	13	8	36	16

Fig. 10-2, Summary of the main performance indicators of the considered ground improvement techniques

The sensible reduction in duration compensates for the substantial increase in costs going from permeation grouting to jet grouting, while the sustainability performance worsens. This is very different for the ground freezing cases where the cost is significantly higher than the ‘grouting’ techniques; the time takes longer, but the sustainability performance improves.

11 Another facet part 2: Social Impact Assessment based on CO2eq emissions based on the outputs of the LCA evaluations

11.1 The Social Cost of Greenhouse Gas Emissions

The social life cycle assessment (S-LCA) is a methodology employed to evaluate the social and sociological dimensions of products and services, as well as their current and potential positive and negative effects throughout their life cycle. This paper explores the many stages involved in the extraction and processing of raw materials, as well as the subsequent processes of manufacture, distribution, usage, reuse, maintenance, recycling, and final disposal. Social life cycle assessment (S-LCA) incorporates both generic and site-specific data, encompassing quantitative, semi-quantitative, and qualitative information. This approach serves as a valuable supplement to environmental life cycle assessment (LCA) and life cycle costing (LCC) methodologies. This strategy has the potential to be utilized independently or in conjunction with other methodologies [Gilchrist and Allouche, 2005].

The social implications and advantages of civil infrastructure projects are closely intertwined with the objectives of sustainable development, such as the promotion of health and safety, poverty eradication, addressing food insecurity, and decreasing disparities [United Nations, 2015]. Nevertheless, existing Social Life Cycle Assessment (S-LCA) approaches frequently rely on qualitative or semiquantitative methodologies, which might introduce a certain level of subjectivity [Neugebauer et al., 2015]. There is a need for recommendations and guidance regarding the optimal approaches to conducting quantitative Social Life Cycle Assessment (S-LCA). This includes the development of methods for assessing a wide range of social indicators in order to compare the societal implications of various technologies used in infrastructure construction, such as different ground improvement methods [Raymond et al., 2021].

As a quantitative output from the presented LCA analyses performed for the different ground improvement treatments, an evaluation of CO2eq emissions as a KPI for the climate change impact has been produced. The connection between this KPI and the overall impact of GHG emissions, also in social terms, has been studied in different policy approaches (the carbon tax concept was born from this kind of discussion [Criqui et al., 2019]. Following Reynolds (2021), our approach quantified the social damage costs from greenhouse gas (GHG) emissions as an indicator of the potential socioeconomic impacts associated with each ground improvement method.

The intermediate estimates of social cost of greenhouse gases (SC-GHG), which were approved by the Interagency Working Group in February 2021 [USEPA, 2017 and IWG, 2016], delineate the association between society and climate change through four key elements: socioeconomics, physical climate, damages, and discounting. Every module functions as a provider of inputs for the subsequent module. Socioeconomic variables exert a significant influence on emissions, hence playing a crucial role in shaping climate alterations. Climatic changes give rise to adverse physical impacts on the climate. The aforementioned damages pertain to economic losses, which are subsequently subjected to a discounting process. The modeling technique employed in this study involves a systematic linear progression through each module towards the estimation of the supply chain greenhouse gas (SC-GHG) emissions. Additionally, the methodology accounts for the interdependencies across various modules, since some outputs from one module serve as inputs to other modules. The interplay between socioeconomics and climate is reciprocal, since climatic conditions and the resulting damages to the climate system have a significant impact on many socioeconomic elements. The figure below illustrates the interconnectedness of these modules and identifies the modules that are crucial in determining the scope of inputs and outputs to be included in the estimations of the SC-GHG [Mendoza, 2018].

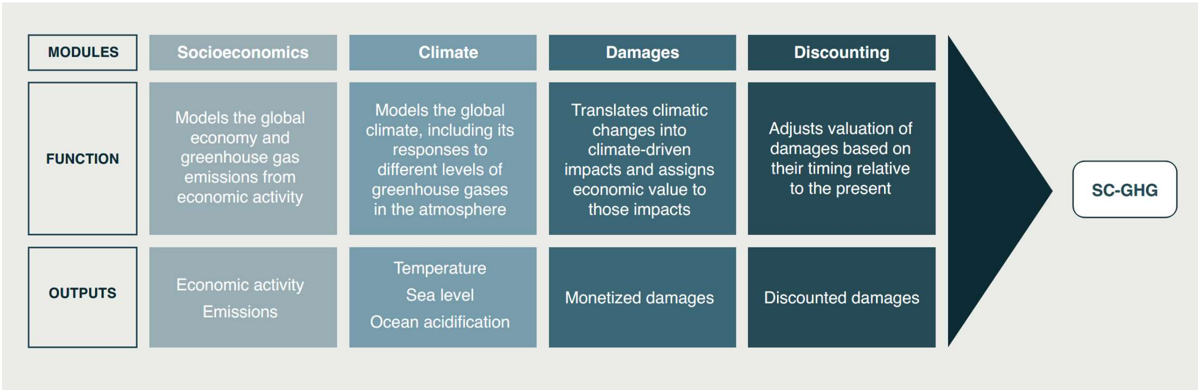


Fig. 11-1, The method for SC-GHG evaluation. (USEPA 2021)

The social cost of greenhouse gas (GHG) emissions, referred to as SC-GHG, is a quantitative assessment of the financial costs associated with the additional environmental damages resulting from incremental increases in GHG emissions during a specific time frame. This estimation was computed for each ground improvement technique by employing the below mathematical equation. [IWG on Social Cost of Greenhouse Gases 2016; Marten et al. 2015a, b and 2021]:

$$SC\text{-}GHG = SC\text{-}CO2 \times \Sigma CO2 + SC\text{-}CH4 \times \Sigma CH4 + SC\text{-}NO2 \times \Sigma N2O$$

where Σ CO2, Σ CH4, and Σ N2O are the CO2, CH4, and N2O emissions (kg) over the life cycle illustrated in the process schemes presented in the previous chapters for each of the techniques that we analyzed.

According to the United States Environmental Protection Agency [USEPA 2021], the anticipated societal cost of carbon dioxide (SC-CO2) was $0.054 per kilogram of CO2 in 2023. While the social cost estimates may not provide a thorough analysis, they serve as a valuable tool for conveying the climate-related consequences of human-caused greenhouse gas emissions in relation to socioeconomic harm. The provided table [USEPA 2021] presents a comprehensive assessment of the whole of greenhouse gas (GHG) emissions. The study and guidelines have incorporated the 3% average discount rate and statistic as an intermediate measure.

Table A-1: Annual SC-CO_2, 2020 – 2050 (in 2020 dollars per metric ton of CO_2)

	Discount Rate and Statistic			
Emissions Year	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	14	51	76	152
2021	15	52	78	155
2022	15	53	79	159
2023	16	54	80	162
2024	16	55	82	166
2025	17	56	83	169
2026	17	57	84	173
2027	18	59	86	176
2028	18	60	87	180
2029	19	61	88	183
2030	19	62	89	187

Tab. 11-1, Social cost of CO2 emissions, different discount rates models (USEPA 2021).

It is interesting to see that the value exhibits an upward trend in response to the escalation of expenditures incurred as one approaches the 2050 limit (target) date. Since the damages from a tonne of CO2 emissions occur over several decades, the discount rate—which represents the trade-off between present and future consumption—plays a significant role in determining the SCC. For initiatives with both intragenerational and intergenerational effects, U.S. federal agencies generally utilize constant real discount rates of 3 and 7 percent each year. However, discounting across very long time horizons involves incredibly complex concerns of physics, economics, philosophy, and law. Given the existing divergence of opinions within the academic literature on the suitable market interest rate to be employed in this particular scenario, coupled with the inherent uncertainty surrounding potential fluctuations in interest rates over time, the interagency working group opted to utilize three fixed discount rates—namely, 2.5, 3, and 5 percent per annum—so as to include a reasonable and believable spectrum.

The data of the table are represented in the curves below where the average discount rate and statistics are represented in different colors.

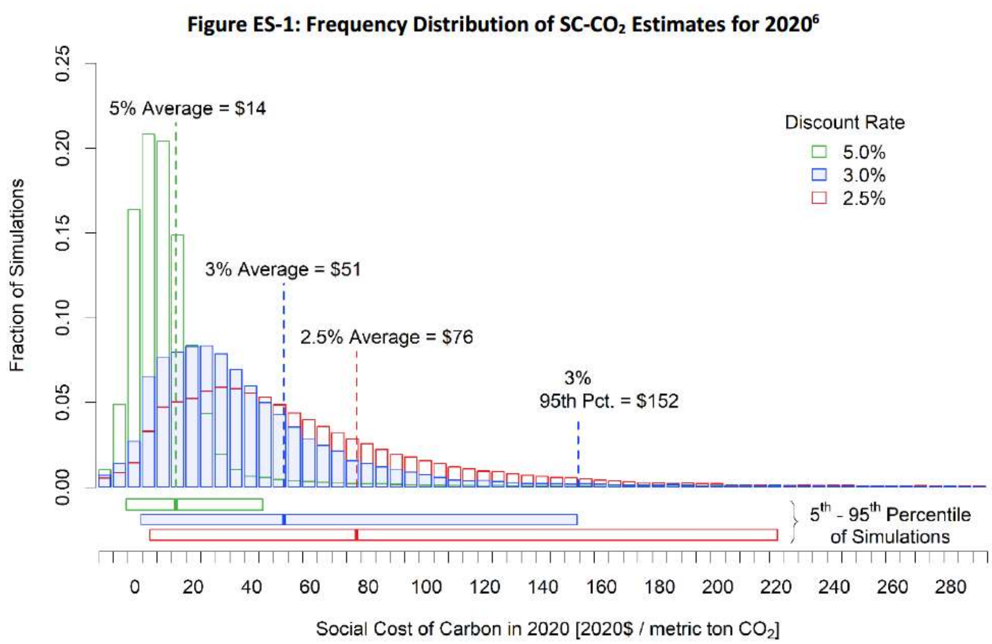


Fig. 11-2, Social cost of CO2 emissions, USEPA 2021.

The estimates of the Social Cost of Carbon (SCC) increase with time due to the anticipation that future emissions would result in greater additional losses. This is attributed to the growth of the economy and the subsequent strain on physical and economic systems, which are predicted to intensify in reaction to increasingly significant climate changes. The determination of these rates is endogenous in nature, since it is influenced by the models themselves. These rates are contingent upon several assumptions, such as the socioeconomic and emissions scenario, the structure of the model, the distribution of parameters, and the discount rate.

11.2 A remark on CO2eq emissions

The Environmental Footprint framework of the EU, as implemented by Simapro, gives as greenhouse gas (or GHG for short) emission KPI for the Climate Change impact category the whole CO2eq emissions, where

CO_2eq means the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas.

A greenhouse gas (GHG) refers to any gas present in the Earth's atmosphere that has the ability to absorb and then re-emit heat, resulting in the retention of thermal energy inside the planet's atmosphere at a higher level than would occur naturally. The primary greenhouse gases present in the Earth's atmosphere include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone.

Greenhouse gases (GHGs) are naturally present in the Earth's atmosphere. However, human activities, such as the combustion of fossil fuels, are contributing to the augmentation of GHG concentrations in the atmosphere. This phenomenon is leading to global warming and subsequent climate change. The Kyoto Protocol is a globally recognized agreement aimed at regulating the emission of greenhouse gases (GHGs) resulting from anthropogenic activities. The specific GHGs subject to regulation within the framework of this treaty are outlined in Table 1. Frequently, these greenhouse gases are commonly known as the "Kyoto gases".

Greenhouse Gas	Global Warming Potential (GWP)
Carbon dioxide (CO_2)	1
Methane (CH_4)	29.8
Nitrous oxide(N_2O)	273
Hydrofluorocarbons (HFCs)	5-14600
Perfluorocarbons (PFCs)	78-12400
Sulfur hexafluoride (SF_6)	25200
Nitrogen trifluoride (NF_3)	17400

Tab. 11-2, Kyoto Gases (IPCC 2021 – 6th Assessment Report Values, GWP

It is noteworthy that various greenhouse gases exhibit distinct atmospheric lifetimes and heat absorption capacities. The term "global warming potential" (GWP) is used to quantify the extent to which a greenhouse gas (GHG) contributes to global warming during a specific timeframe, often spanning 100 years. The Global Warming Potential (GWP) is a metric utilized to quantify the relative warming potential of greenhouse gases (GHGs). Carbon dioxide (CO_2) serves as the reference gas, assigned an index value of 1. The GWP of all other GHGs is determined by the extent to which they contribute to global warming in comparison to CO_2, expressed as a multiple of its warming effect. For instance, the global warming potential (GWP) of methane is 29.8, indicating that 1 kilogram of methane contributes 29.8 times more warmth over a 100-year timeframe compared to 1 kilogram of carbon dioxide (CO_2).

Carbon dioxide (CO_2) is the predominant greenhouse gas (GHG) generated by anthropogenic activity, both in terms of its sheer volume of emissions and its overall contribution to the phenomenon of global warming. Consequently, the designation "CO_2" is occasionally employed as an abbreviated representation encompassing all greenhouse gases. Nonetheless, this practice can lead to ambiguity, and a more precise manner of denoting a group of GHGs collectively is to utilize the phrase "carbon dioxide equivalent" or "CO_2e" (elucidated subsequently).

Due to its significant role as a greenhouse gas, carbon dioxide (CO_2) is often prioritized in greenhouse gas (GHG) evaluations or reports, while other greenhouse gases are overlooked. Consequently, this selective approach might result in an underestimation of the overall impact of global warming. Greenhouse gas inventories exhibit enhanced comprehensiveness when they encompass the entirety of greenhouse gases (GHGs) rather than only focusing on carbon dioxide (CO_2).

Hence, the term "Carbon dioxide equivalent" or "CO_2eq" is employed to denote various greenhouse gases using a standardized unit. The term "CO_2eq" represents the quantity of carbon dioxide (CO_2) that would provide a comparable global warming effect, regardless of the specific greenhouse gas and its amount.

The quantification of greenhouse gas (GHG) emissions may be represented as carbon dioxide equivalent (CO2eq) by multiplying the quantity of each GHG by its respective global warming potential (GWP). For instance, when 1 kilogram of methane is released, it may be equivalently represented as 29.8 kilograms of carbon dioxide equivalent (1 kilogram of CH4 multiplied by 29.8 equals 29.8 kilograms of CO2eq).

The word "CO2eq" holds significant use for several reasons. Firstly, it enables the consolidation of several greenhouse gases into a singular numerical value, facilitating a comprehensive representation of gas bundles. Additionally, it facilitates the straightforward comparison of distinct bundles of greenhouse gases by quantifying their collective influence on global warming. Nevertheless, it is imperative to use prudence when juxtaposing CO2eq aggregates, since it is crucial to ascertain that the contrasted totals encompass identical greenhouse gases (GHGs), so ensuring the feasibility of making equitable comparisons.

Taking into consideration the aforementioned factors, the societal cost of CO2 emissions has been determined by conducting a life cycle assessment (LCA) and evaluating the CO2 equivalent (CO2eq) values. In light of the intricate economic developments following the Covid-19 pandemic and other events like as the Energy and Materials Shortage, Ukraine War, and Inflation Rise, it has been determined that maintaining the 2020 reference for the Dollar/Euro currency is the most prudent course of action.

11.3 Social Impact of CO2eq emissions evaluation based on the performed LCA

The following table presents a summary of the outcomes obtained from the baseline reference and the sensitivity runs. The carbon dioxide equivalent (CO2eq) values for each approach have been multiplied by a factor of 54, which has been translated to Euro using the 2023 currency exchange rate of 0.94. After assessing the magnitude of the societal cost, the proportion of this value in relation to the total value of the technology is determined.

PERMEATION GROUTING			Social Cost of CO2, 2020-2050		
Impact category	Quantity Baseline	Unit	$ 2023 per 1000kg of CO2	Baseline Social total cost (CO2eq)	% of project cost
Climate change	44162,18157	kg CO2 eq	54	2385	2,1%

JET GROUTING SINGLE FLUID			Social Cost of CO2, 2020-2050		
Impact category	Quantity Baseline	Unit	$ 2023 per 1000kg of CO2	Baseline Social total cost (CO2eq)	% of project cost
Climate change	297937,3618	kg CO2 eq	54	16089	7,7%

JET GROUTING DOUBLE FLUID			Social Cost of CO2, 2020-2050		
Impact category	Quantity Baseline	Unit	$ 2023 per 1000kg of CO2	Baseline Social total cost (CO2eq)	% of project cost
Climate change	384881,1106	kg CO2 eq	54	20784	7,9%

BRINE FREEZING			Social Cost of CO2, 2020-2050		
Impact category	Quantity Baseline	Unit	$ 2023 per 1000kg of CO2	Baseline Social total cost (CO2eq)	% of project cost
Climate change	45377,18315	kg CO2 eq	54	2450	0,4%

NITROGEN FREEZING			Social Cost of CO2, 2020-2050		
Impact category	Quantity Baseline	Unit	$ 2023 per 1000kg of CO2	Baseline Social total cost (CO2eq)	% of project cost
Climate change	12081,5316	kg CO2 eq	54	652	0,1%

Tab. 11-3, Evaluation of the Social cost of CO2eq emissions based on the LCA analyses performed

The significance of the societal cost escalates in the context of jet grouting schemes, whereas it diminishes for freezing approaches.

In order to provide a comprehensive perspective on the quantitative and monetary assessment of the social costs associated with greenhouse gas (GHG) emissions, it is essential to consider this amount in conjunction with the total cost of the intervention for each technique, as discussed in the preceding chapter. Additionally, it is important to take into account the Envision/DNSH scores and the duration of the project, as the latter often plays a crucial role in the ultimate decision-making process. In light of the aforementioned considerations, the subsequent table provides a comprehensive summary of the envision/DNSH scoring, project cost, project time, and societal costs associated with CO2eq emissions subsequent to the implementation of the suggested three-phased methodology.

CATEGORY	PERMEATION GROUTING	JET GROUTING SINGLE FLUID	JET GROUTING DOUBLE FLUID	BRINE FREEZING	NITROGEN FREEZING
Envision rating (% total score)	45%	39%	31%	49%	49%
DNSH rating (% total score)	48%	41%	33%	51%	48%
Project cost (€ 2020)	122265,6	223140	281276	604752	586500
Project duration (days)	23	13	8	36	16
Social cost (€ 2023 - CO2eq)	2385	16089	20784	2450	652

Tab. 11-4, Overview of the performance for each ground improvement technique technique

12 The ground improvement case studies through the lenses of the three-step methodology, an overview of the results

The five ground improvement case studies have been assessed within the framework based on the Envision protocol and the EU Regulation DNSH criteria. Once a first qualitative assessment was implemented, the LCA analyses presented in the paper allowed for refinement and final scoring. We then evaluated the cost and schedule of the five techniques and a social impact estimate through GHG emissions.

The following paragraphs present an overview of the results developed so far.

12.1 Summary of the results for the first phase of the method

The scores for the Envision sustainability indicators that are part of the framework made for geotechnics and ground improvement processes are shown below in a table. The evaluation is then extended to the DNSH requirements. The last two rows rank each treatment with the total Envision and DNSH scores.

	Maximum ENVISION Points Available	Minimum ENVISION Points Available	Score Permeation grouting		Score Single fluid Jet Grouting		Score Double fluid Jet Grouting		Score Brine Ground Freezing		Score Nitrogen Ground Freezing	
QL1.4	12	1	1	8%	1	8%	1	8%	3	25%	3	25%
QL1.6	8	1	1	13%	1	13%	1	13%	2	25%	2	25%
LD1.4	18	3	6	33%	6	33%	3	17%	6	33%	6	33%
LD3.3	14	5	7	50%	7	50%	7	50%	7	50%	7	50%
RA1.1	12	3	12	100%	12	100%	12	100%	12	100%	12	100%
RA1.2	16	4	9	56%	9	56%	6	38%	6	38%	6	38%
RA1.4	16	4	7	44%	4	25%	4	25%	10	63%	10	63%
RA2.2	12	1	8	67%	4	33%	1	8%	8	67%	8	67%
RA2.3	24	5	15	63%	15	63%	15	63%	15	63%	15	63%
RA3.3	8	1	3	38%	1	13%	1	13%	5	63%	5	63%
NW2.4	20	2	2	10%	2	10%	2	10%	2	10%	2	10%
NW3.5	8	3	3	38%	3	38%	3	38%	3	38%	3	38%
CR1.1	20	5	15	75%	10	50%	5	25%	15	75%	15	75%
CR1.2	26	3	13	50%	13	50%	8	31%	18	69%	18	69%
CR1.3	18	2	2	11%	2	11%	2	11%	2	11%	2	11%
Envision	232	43	104	45%	90	39%	71	31%	114	49%	114	49%
DNSH	348	68	166	48%	144	41%	114	33%	176	51%	167	48%

Tab. 12-1, First Phase Output: The sustainability performance of the five ground improvement technique under the Envision and the DNSH scoring.

Points are awarded exclusively when the standard criteria is surpassed. Based on the Envision award criteria, which allocate a minimum achievable score of 20% and categorize scores between 20-29% as verified, 30-39% as Silver, 40-49% as Gold, and 50% and above as Platinum, the performance of the techniques examined indicates that they surpass the verified threshold. Notably, ground freezing demonstrates a performance that approaches the Platinum level.

The results are then plotted in a radar format (see the next figure) in order to emphasize the 'distribution' of the scores with respects to the indicators.

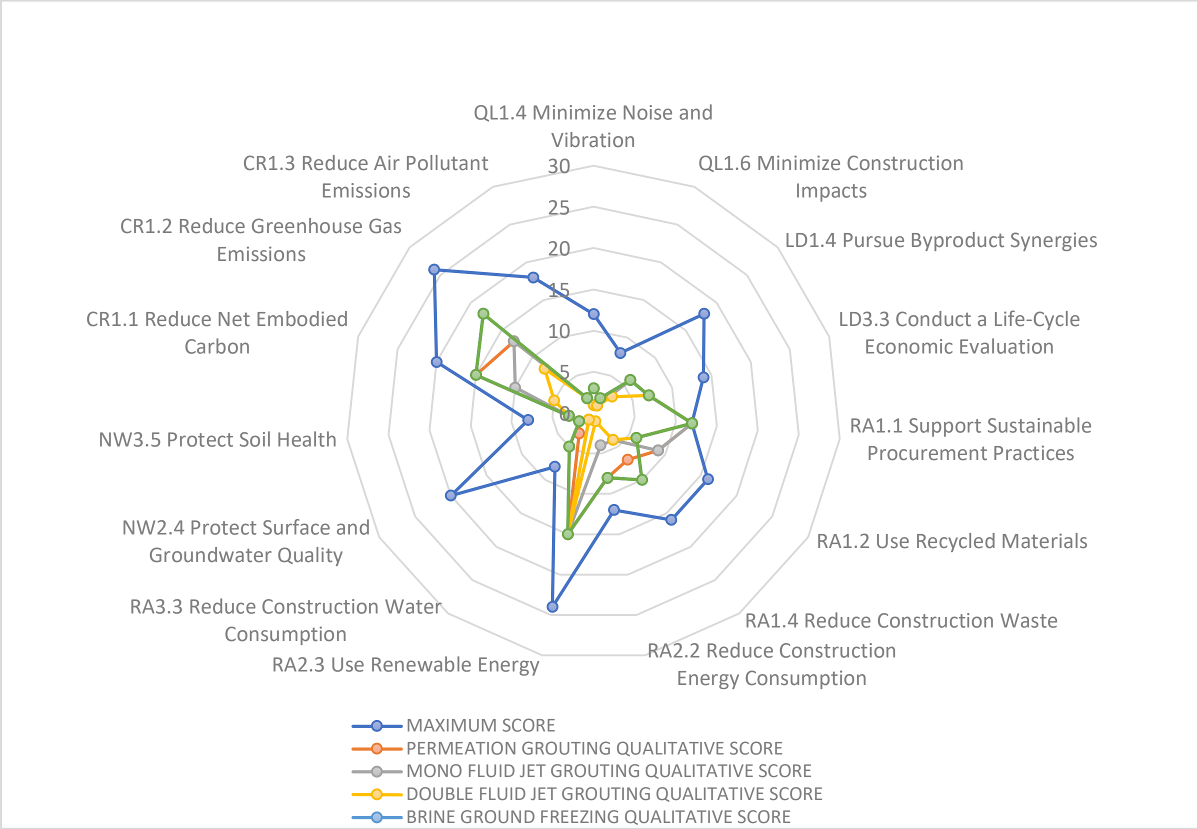


Fig. 12-1, First Phase Output: The sustainability performance of the five ground improvement techniques under the Envision and the DNSH scoring. A comparison through the radar diagram view.

The diagram schows that, when taking into account the characteristics of the indicators of the Envision/DNSH framework that have been adapted to ground improvement techniques, the area in which to search for more opportunities of good sustainability performances is that which is related to Climate and Resilience (CR1.x, focused on emissions), Resource Allocation (RA1.x, focused on materials and RA2.x focused on energy), and Leadership (LD1.X, focused on collaboration between production sectors). These are the aspects of the process that will receive special focus during the second phase of the approach, which is the life cycle evaluation.

12.2 Summary of the results for the second phase of the method

The following graphs will examine the distinct performances of the five treatments. The LCA assessments provide an environmental assessment of each approach and the comparative performance, from the perspective of several environmental impact categories, of each type of treatment. Taking into consideration the relevant facts pertaining to each treatment, these analyses facilitate the implementation of two primary tasks during the development of a project:

1. The environmental performance is assessed using quantitative measures and compared to other methodologies, enabling strategic decision-making about the construction process.
2. Given the sensitivity to each important impact category and the significant influence exerted by individual materials, equipment, and process phases, there is much opportunity for additional analysis

and extra considerations. These will be explored in detail in the next chapter, where the results are discussed.

The comparison is conducted based on the baseline analysis as a single score representation.

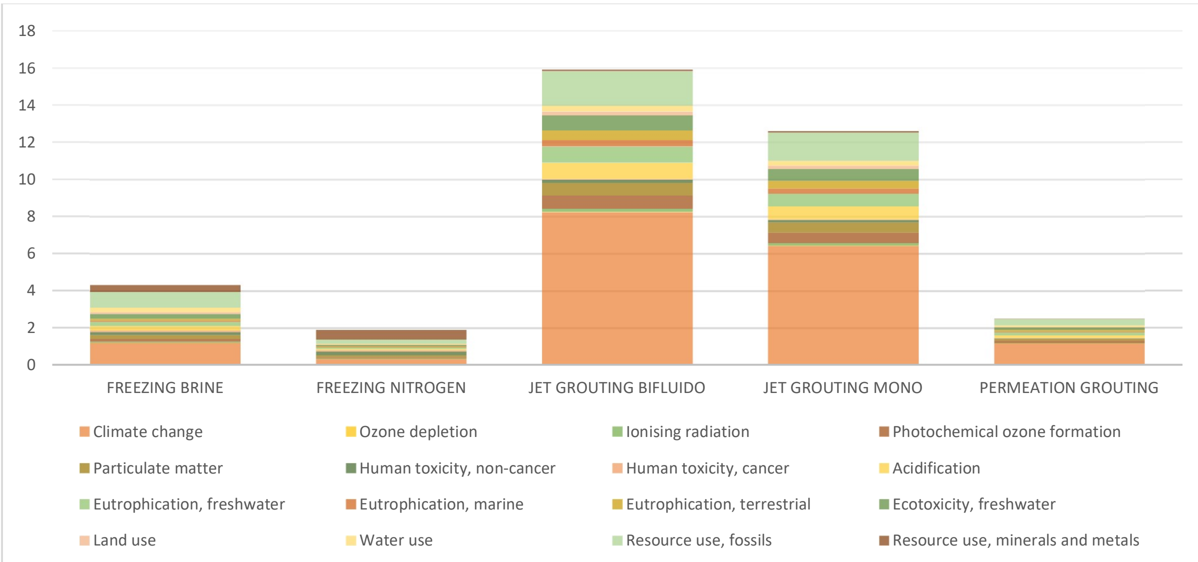


Fig. 12-2, Case studies techniques comparison: impact, single point/score view.

Upon doing a comparative analysis of the cumulative scores obtained from the five case studies, it becomes evident that the nitrogen freezing method has the least significant impact. The primary factors contributing to this phenomenon are climate change, resource depletion, and the water-related consequences associated with cement manufacturing and utilization. The grout component performance in permeation grouting is balanced (when compared to brine freezing) by the material and energy relevance of the 'freezing' effort needed to keep brine in circulation. Finally, jet grouting, that represents a strong and effective treatment, pays a high sustainability penalty due to the large need for energy and grout cement-based mix.

The following table allows for the comparison between the different techniques: the heat map highlights (in red) the highest values for the quantitative KPIs of each impact category and confirms the above evaluations.

Impact category	Unit	PERMEATION GROUTING	JET GROUTING SINGLE FLUID	JET GROUTING DOUBLE FLUID	FREEZING BRINE	FREEZING NITROGEN
Climate change	kg CO2 eq	44162,18116	246215,44830	316196,39990	45377,18269	12081,53161
Ozone depletion	kg CFC11 eq	0,00279	0,01183	0,01422	0,00685	0,00165
Ionising radiation	kBq U-235 eq	2115,31387	11200,80211	13923,23464	5918,79626	2020,55654
Photochemical ozone formation	kg NMVOC eq	100,18710	488,39035	608,09381	122,45663	50,96231
Particulate matter	disease inc.	0,00080	0,00364	0,00452	0,00133	0,00084
Human toxicity, non-cancer	CTUh	0,00027	0,00155	0,00201	0,00206	0,00229
Human toxicity, cancer	CTUh	0,00001	0,00003	0,00004	0,00007	0,00008
Acidification	mol H+ eq	122,69145	627,28454	781,53838	221,86829	57,45410
Eutrophication, freshwater	kg P eq	9,42141	39,20071	50,10546	12,98632	4,46386
Eutrophication, marine	kg N eq	37,41535	182,96914	229,02614	41,12721	16,08678
Eutrophication, terrestrial	mol N eq	393,50655	1976,13326	2471,45650	443,28549	167,50348
Ecotoxicity, freshwater	CTUe	273202,00878	1417097,26782	1786505,06989	567979,18605	145972,33367
Land use	Pt	323969,19188	1864116,81548	2318539,97682	1073906,92763	322307,70222
Water use	m3 depriv.	11477,57963	35047,85458	41721,04968	31698,83055	5710,29780
Resource use, fossils	MJ	264587,27406	1189666,35757	1452697,14610	667564,16087	175307,43694
Resource use, minerals and metals	kg Sb eq	0,02053	0,05804	0,06998	0,31618	0,42718
Climate change - Fossil	kg CO2 eq	44070,27949	245697,90639	315550,19110	45124,85995	12045,89053
Climate change - Biogenic	kg CO2 eq	60,92449	337,16252	413,95098	209,80594	23,22929
Climate change - Land use and LU change	kg CO2 eq	30,97718	180,37939	232,25781	42,51680	12,41178

Tab. 12-2, Case studies techniques comparison: impact, characterization values.

12.3 Summary of the results for the third phase of the method

The following table summarizes the final evaluation with the Envision/DNSH framework, based on the LCA baseline and sensitivity runs. Each score has been validated through the quantitative data from LCA analyses. The final scores change as described in the previous chapter.

	Maximum ENVISION Points Available	Minimum ENVISION Points Available	Score Permeation grouting		Score Single fluid Jet Grouting		Score Double fluid Jet Grouting		Score Brine Ground Freezing		Score Nitrogen Ground Freezing	
QL1.4	12	1	1	8%	1	8%	1	8%	3	25%	3	25%
QL1.6	8	1	1	13%	1	13%	1	13%	2	25%	2	25%
LD1.4	18	3	6	33%	6	33%	3	17%	6	33%	6	33%
LD3.3	14	5	7	50%	7	50%	7	50%	7	50%	7	50%
RA1.1	12	3	12	100%	12	100%	12	100%	12	100%	12	100%
RA1.2	16	4	9	56%	9	56%	6	38%	6	38%	6	38%
RA1.4	16	4	7	44%	4	25%	4	25%	10	63%	10	63%
RA2.2	12	1	8	67%	4	33%	1	8%	8	67%	12	100%
RA2.3	24	5	15	63%	15	63%	15	63%	15	63%	15	63%
RA3.3	8	1	3	38%	1	13%	1	13%	5	63%	3	38%
NW2.4	20	2	2	10%	2	10%	2	10%	2	10%	2	10%
NW3.5	8	3	3	38%	3	38%	3	38%	3	38%	3	38%
CR1.1	20	5	10	50%	10	50%	10	50%	15	75%	10	50%
CR1.2	26	3	8	31%	8	31%	8	31%	13	50%	8	31%
CR1.3	18	2	2	11%	2	11%	2	11%	2	11%	2	11%
Envision	232	43	94(104)	41% (45%)	85(90)	37%(39%)	76(71)	33%(31%)	109(114)	47%(49%)	101(114)	44%(49%)
DNSH	348	68	151	43%	139	40%	124	36%	171	49%	149	43%

Tab. 12-3, Case studies comparison, impact, characterization values.

The line with the total Envision scores has in brackets the corresponding evaluation of the first phase. Apart from the nitrogen freezing technique, the others has been slightly reduced after the quantitative LCA assessment.

12.4 Overview of the three phased method results and the LCCA and SC-GHG evaluations

As an integration of the sustainability performance evaluation done with the three phased method, the cost and the social impact aspects have been explored.

In order to provide a comprehensive perspective on the quantitative and monetary assessment of the social costs associated with greenhouse gas (GHG) emissions, it is essential to consider this amount in conjunction with the total cost of the intervention for each technique, as discussed in the preceding chapter. Additionally, it is important to take into account the Envision/DNSH scores and the duration of the project, as the latter often plays a crucial role in the ultimate decision-making process. In light of the aforementioned considerations, the subsequent table provides a comprehensive summary of the envision/DNSH scoring, project cost, project time, and societal costs associated with CO2eq emissions subsequent to the implementation of the suggested three-phased methodology.

CATEGORY	PERMEATION GROUTING	JET GROUTING SINGLE FLUID	JET GROUTING DOUBLE FLUID	BRINE FREEZING	NITROGEN FREEZING
Envision rating (% total score)	45%	39%	31%	49%	49%
DNSH rating (% total score)	48%	41%	33%	51%	48%
Project cost (€ 2020)	122265,6	223140	281276	604752	586500
Project duration (days)	23	13	8	36	16
Social cost (€ 2023 - CO2eq)	2385	16089	20784	2450	652

Tab. 12-4, Overview of the performance for each ground improvement technique technique

13 Discussion of the results and further steps

13.1 The value of cradle to site process sustainability analysis for the construction ecosystem: is there a 'right/better' solution?

13.1.1 At the strategic level of the sustainability performance

The overall sustainability scenario that comes from the presented results is, on the one hand, broad and, on the other hand, simple and direct to interpret.

Each process has been framed through the setting of the Envision/DNSH indicators that we selected for geotechnics and ground improvement construction processes. This allowed us to identify the hot spots of the techniques but also to put them in a more holistic sustainability perspective.

Then, each process has been sized and decomposed into its material, energy, technology-specific components and contributions and subsequently quantified. The LCA analyses allow for digging into the construction practices themselves; baselines and sensitivities have been developed to compare each construction process to the others. The variety of the impacts (chosen among the European Environmental Footprint 3.0 framework) widens the decision maker's sight. It opens up to evaluations in the categories of climate change, resource depletion, human toxicity, and many others that pop up depending on the nature of the specific construction process.

This approach aims to provide quantified support to decisions that integrate those from the 'well-known' and commonly used structural, geotechnical, and constructability analyses. As a consequence of considering the results that have been presented, different decision paths might be taken regarding logistics, materials, equipment, and schedule…and this happens at the level of the single practice. However, this 'impact' information is also needed at the strategic level of the project (funding, feasibility, community engagement…), and its role can be game-changing for the future of a civil infrastructure project.

13.1.2 At the operational level of the single technique performance (what are we getting from the LCA analyses).

As an extreme synthesis, comparing the technologies, it comes out a ranking in terms of impact (from the lowest single point to the highest): ground freezing with nitrogen, ground freezing with brine, permeation grouting, jet grouting bi-fluid and jet grouting single-fluid. This is mainly due to the role played by cement related materials (resource depletion, air quality, toxicity) and by drilling (diesel or electricity powering). Other elements could play a mitigative role (use of steel for pipes and rods, transport). There is no right or wrong technology, this analysis provides a set of questions that can be addressed only in conjunction with the structural, geotechnical and construction approach. The following table details the relevance of each impact category among the different cases.

Impact category	Unit	PERMEATION GROUTING	JET GROUTING SINGLE	JET GROUTING DOUBLE FLUID	FREEZING NITROGEN	FREEZING BRINE
Total	%	100	100	100	100	100
Climate change	%	46,1	50,9	51,7	16,7	27,4
Ozone depletion	%	0,1	0,1	0,1	0,1	0,2
Ionising radiation	%	1,0	1,1	1,0	1,3	1,6
Photochemical ozone formation	%	4,7	4,6	4,5	3,2	3,3
Particulate matter	%	4,8	4,4	4,3	6,7	4,7
Human toxicity, non-cancer	%	0,9	1,0	1,0	9,8	3,8
Human toxicity, cancer	%	0,4	0,3	0,3	5,1	2,0
Acidification	%	5,5	5,6	5,5	3,4	5,7
Eutrophication, freshwater	%	6,6	5,4	5,5	4,1	5,3
Eutrophication, marine	%	2,3	2,2	2,2	1,3	1,4
Eutrophication, terrestrial	%	3,3	3,3	3,3	1,9	2,2
Ecotoxicity, freshwater	%	4,9	5,1	5,1	3,5	5,9
Land use	%	1,3	1,4	1,4	1,7	2,4
Water use	%	3,4	2,1	1,9	2,3	5,5
Resource use, fossils	%	13,6	12,1	11,7	12,0	19,8
Resource use, minerals and metals	%	1,0	0,5	0,5	27,0	8,7

Tab. 13-1, Case studies comparison, impacts, percentages per treatment.

Both the first phase of the assessment and the results of the baseline case of the treatments point on these elements to focus on for further sensitivity analyses:

- Energy focus: Improve consumption (a) reducing power production from diesel engines, (b) using electricity coming from providers that use a mix of production that includes renewable sources.
- Transportation focus: Improve the rating of diesel transportation fueled trucks.
- Material focus: for cement, reduce the content in clinker (through pozzolana or fly ash additions).

The sensitivity analyses performed for each technique used the data availability of the Ecoinvent database, more in detail each baseline has been expanded including these sustainability upgrades:

- Energy: use of an energy mix 70% fossil and 30% renewable (for instance hydro coming from run off river generation), through the Ecoinvent string: Electricity, high voltage {IT}| electricity production, hydro, run-of-river | APOS, U.

- Cement: use of Pozzolana-based cement instead of Portland-based cement, through the Ecoinvent string: Cement, pozzolana and fly ash 11-35% {Europe without Switzerland}| market for cement, pozzolana and fly ash 11-35% | APOS, U.

- Steel: use of iron coming from scrap, through the Ecoinvent string Iron scrap, unsorted {RoW}| steel production, electric, low-alloyed | APOS, U.

- Transportation: use of trucks Euro6 instead of Euro5, through the Ecoinvent string: Transport, freight, lorry 16-32 metric ton, EURO6 {RER}| transport, freight, lorry 16-32 metric ton, EURO6 | APOS, U.

The analysis is only indicative, because of the 'generic' nature of the data coming from the Ecoinvent database, and more could be done using customized EPDs or material oriented LCAs provided by suppliers, still this sensitivity calculation can give a measure of how much the sustainability performance of the technique could be improved in the light of the suggestions coming from the Envision indicators and the LCA baseline analysis.

		PERMEATION GROUTING	JET GROUTING SINGLE FLUID	JET GROUTING DOUBLE FLUID	BRINE FREEZING	NITROGEN FREEZING
Impact category	Unit	S/B (%)	S/B (%)	S/B (%)	S/B (%)	S/B (%)
Climate change	kg CO2 eq	-16,38%	-18,15%	-17,45%	-26,44%	-16,72%
Ozone depletion	kg CFC11 eq	-9,86%	-15,02%	-13,18%	-25,97%	-15,86%
Ionising radiation	kBq U-235 eq	-13,73%	-16,30%	-13,35%	-31,60%	-34,48%
Photochemical ozone formation	kg NMVOC eq	-13,40%	-17,98%	-19,28%	-24,41%	-16,65%
Particulate matter	disease inc.	-10,31%	-15,05%	-16,66%	-29,61%	-31,59%
Human toxicity, non-cancer	CTUh	-16,13%	-17,81%	-17,18%	-62,60%	-65,58%
Human toxicity, cancer	CTUh	-8,81%	-15,03%	-17,39%	-56,26%	-58,58%
Acidification	mol H+ eq	-14,67%	-18,24%	-17,40%	-27,29%	-19,66%
Eutrophication, freshwater	kg P eq	-7,64%	-12,01%	-9,59%	-30,07%	-29,46%
Eutrophication, marine	kg N eq	-13,08%	-17,60%	-18,77%	-24,39%	-15,93%
Eutrophication, terrestrial	mol N eq	-14,10%	-18,31%	-19,53%	-24,84%	-16,84%
Ecotoxicity, freshwater	CTUe	-17,09%	-19,93%	-17,65%	-27,42%	-19,48%
Land use	Pt	-19,39%	-20,24%	-16,25%	-26,85%	-11,78%
Water use	m3 depriv.	-6,97%	-14,27%	-5,81%	-31,40%	-29,61%
Resource use, fossils	MJ	-11,61%	-16,31%	-13,71%	-27,40%	-20,10%
Resource use, minerals and metals	kg Sb eq	-8,16%	-17,76%	-14,06%	-21,93%	-17,07%

Tab. 13-2, Summary of the reduction of impact for each category and technique (in p.c.).

The table above represents the reduction of impact per category and for each technique expressed in percentage of reduction in the sensitivity analysis with respect to the baseline value.

The three focus areas have different relative effects depending on the treatment: renewables are very useful for freezing techniques that have a high need for energy, reduction of clinker in cement is relevant for grouting techniques, while electricity powered devices and more performing diesel engines have a quite transversal beneficial effect.

13.1.2.1 Not only environmental effects

The cost and schedule evaluation and the social effect estimate of GHG emissions add three more perspectives to the environmental one and, in some sense, render complete the sustainability assessment, bringing in the economic and the social pillars.

CATEGORY	PERMEATION GROUTING	JET GROUTING SINGLE FLUID	JET GROUTING DOUBLE FLUID	BRINE FREEZING	NITROGEN FREEZING
Envision rating (% total score)	45%	39%	31%	49%	49%
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Project cost (€ 2020)	122265,6	223140	281276	604752	586500
Project duration (days)	23	13	8	36	16
Social cost (€ 2023 - CO2eq)	2385	16089	20784	2450	652

Tab. 13-3, Overview of the performance for each ground improvement technique.

Among the treatments, jet grouting allows for a strong schedule optimization (13 and 8 days overall) that is counterbalanced by a weaker environmental performance (39% and 31% Envision scores). Social costs are the highest as well (16k€ and 20k€). Freezing techniques are more cost intensive (more than 500k€) and in the case of brine take longer (36 days compared to 16 days with nitrogen) but reduce heavily the environmental (Envision score 49%) and the social (5,4k€ and 0,6k€) impact.

13.2 Possible limitations of the method. Potential for fine tuning of the construction processes: sustainability sensitivity analysis through LCA

The previous analyses have highlighted that when it comes to materials, energy, recycling there is large room for improving the sustainability performance of the traditional construction processes and to exploit the sustainability character of the more innovative technologies. The limitation of this approach lies in the inventory of the LCA analysis and in the fact that, being the existing databases more oriented towards products than processes, and particularly distant from construction processes for infrastructure, they tend to be abstract and not enough representative.

How to respond to this need? The source of more refined data should be the industry in itself rather than general institutions that tend to give ‘average’ information. Thanks to the cited push for giving value to the environmental footprint of products, the Environmental Product Declaration have started to gain place in the infrastructure construction market during the last ten years.

With reference to the matter that we are treating in this article, it is the cement industry that is ahead in this moment. Cement producers, in an alliance with concrete producers, are nowadays ready to deliver EPD for concrete mixes in a cradle to site format, sized right at (and assessed with a specific LCA) the gate of the construction site work. The ability of incorporating this cradle to gate site specific information into our analyses is the next step of our research. When this is possible and done, the chance of fine-tuning analyses with specific data represents the next frontier of our approach and will allow a comprehensive impact assessment that, together with the structural and the geotechnical analyses, gives the chance to quantify sustainability and to make it a design tool like the usual others.

Focusing on cradle to gate or cradle to site means to focus on the construction phase. This is a good approach for everything that is related (material, schedule, equipment, etc.) to the feasibility and it is based on the assumption that the majority of the impacts take place in this phase. While this is undoubtedly true, it may penalize those materials that play a role during the whole life cycle of an infrastructure and that may produce more impacts (or more savings) during the operation and maintenance life cycle phases. In these cases, this should be kept into consideration by extending the length of the LCA to the next phases or by double checking the decisions that are suggested by the cradle to site LCA and seeking consequences on the operational or maintenance design and planning aspects. A typical example is the case of cement: while in our ground improvement cases grout mix operates until the final artifact is put into place, there may be cases in which grout plays a ‘definitive’ role for the infrastructure and durability or maintenance reasons may drive the choices toward an impacting mix. Anyway, the proposed approach allows for informed decisions: it will be possible to quantify the reasons for a less sustainable choice that may be compensated elsewhere in the project.

As a final consideration, this approach can be applied also to any other geotechnical technology: piles, micropiles, foundations, retaining structures. There is a whole world of impacting technologies that can be refined under the sustainability point of view and that needs a quantified and transparent approach in order to penetrate the construction and procurement decision makers.

The aim of this thesis, and the methodology in three steps behind it, is to support the construction industry and the decision makers (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, for both the general view of the project and the basic and critical construction processes, in a way that can be transparently shared and used to claim for true sustainable measures adopted in their projects.

For too long the development of LCA analyses, EPDs, protocols, have been closer to the Academia than to the industry; actaully this 'simple' use of LCA coupled with a very pragmatic protocol, like Envision, can really induce a permeation of LCA into the day to day design and construction practice. A link with the DNSH and the EU Regulation criteria has been explained, that helps to measure the sustainable approach as the finance world needs it in these days and, again, this can help suppliers to be transparently compliant to owners, investors and customers requirements.

The qualitative level of the method, that focuses the application of the Envision protocol to a specific construction process, in our case study the 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 economic, environmental, social goals: noise and vibration, recycled materials use, waste reuse, water conservation, energy consumption, resource scarcity, economic value, sustainable procurement practices, construction impacts on communities, air quality…as one can see it is not only about greenhouse emissions. The method that has been used to focus Envision and the DNSH EU framework to the ground improvement case can be used to further broaden the range of sustainability indicators. The key principle is that the metrics to be applied 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) and are commonly adopted by an international community of stakeholders.

The next step, the adoption of a LCA, brings in a deeper knowledge and the quantitative analysis needed to size the assessment. The range of impacts and the opportunity to compare different construction strategies (material and technology adoption, timing and schedule, phasing, etc.) allow for a fine tuning of the process in itself under the environmental point of view (the social and economic components are embedded in the protocol application) and can truly identify critical and hot points 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 suitable proposals.

There are two limitations that can be identified so far in the method.

The first one is also its strength. We chose to limit the analysis to the cradle to gate or the cradle to site phases. This is mainly because in the case of civil infrastructure the larger part of the impact happens during the phases of construction (and of production of the construction 'ingredients'), while 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). About reuse, we think that for the case of civil infrastructure it has to coincide with regenerative maintenance that brings an old infrastructure back to service. The cases of demolition and reconstruction will be more and more rare, due to the very high investment that has been done in the creation phases [Huang et al., 2009]. This limitation can be solved in two ways (that will be 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 in a simple way (Chiola, 2022).

The second limitation is the area of greater research from our side in this moment. LCA are normally based on 'standardized' data coming from international and recognized databases that tend to be too far from 'reality' when it comes to construction sites. This is unavoidable when the analysis through LCA spans over the entire life of an infrastructure: the number of products and processes involved and related data is so large that simplification, average, statistics becomes a must. But 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 coming from the EPD can be used to feed the LCA and to fine tune the analysis comparing different 'real' ingredients to the construction process [Soust-Verdaguer, 2023]. Once this is done, the analyst could compare products that enhanced their green supply chain and increase the score of the impact and the Envision evaluation. This can be done for concrete, asphalt, reinforcement … for all the main players of an infrastructure impact. Our current research involves Industry (through producers associations, owners, contractors), Academia (for methods) and Software Producers (to facilitate access to EPD). More to say in the next publications [Susani et al., 2023].

Keeping the focus on geotechnics, this approach can be applied to the full range of ground improvement techniques [Susani et al., 2023] comparing permeation grouting, jet grouting (with single- and bi- fluid systems), ground freezing (with brine or nitrogen).

14 Conclusion

To support decision making of the construction industry stakeholders, this thesis develops a method that focuses the LCA analyses on cradle to site construction processes in order to support decision makers and stakeholders of the infrastructure industry.

LCA is here used in the aim of focusing on specific and realistically modelled processes of the construction industry, and a case study has been developed for ground improvement techniques, that are critical to success of underground urban development and very sensitive to technology innovation and development.

The limitation of LCA to cradle-to-gate and cradle-to-site models, is counterbalanced by the opportunity to make the inventory phase of the analysis that is as close as possible to the reality of the project and to track the impact role of each step of the specific construction process.

This approach can be key 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, quantitatively show their sustainability characteristics;
- on the other side, a process based LCA can stimulate easy methodology fine tuning and alternatives evaluation through sustainability lenses and metrics.

This is a real opportunity to sustain a green supply chain in the construction ecosystem.

As further research developments we will focus on:

- building a realistic inventory for ground improvement techniques and, more in general, geotechnical and underground construction;
- extending the approach to other geotechnical relevant processes, other than ground improvement techniques [Susani et al., 2023].

This is a real chance to integrating sustainability in the ‘normal’ and day-to-day geotechnical design and construction practice.

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16 Appendix: The Environmental Product Declaration (EPD)

16.1 What is an EPD and which is its relationship with LCA

The study of the life cycle (LCA, Life Cycle Assessment) of a product or service is made up of numerous calculations and assumptions that constitute a very "large" dossier, with numerous pages and difficult to read for the user. For this reason, the international standard ISO 14025 "Environmental labels and declarations - Type III environmental declarations - Principles and procedures" has provided for the development of a document that can facilitate the dissemination on the market of the LCA study conducted and the results obtained through an effective graphical representation and an easily interpretable data set [Rangelov, 2020 and 2021].

This is how the Environmental Product Declaration EPD was born (a term that derives from the English Environmental Product Declaration), which is defined as:

- an environmental label (therefore a representation of an environmental aspect);
- type III, which differs from those of type I (such as the Eco Label, with minimum acceptability thresholds) and those of type II (self-declarations).

The EPD represents an essential form of communication aimed at disseminating the environmental impacts relating to the production of a product/service and determined by a life cycle study.

The life cycle phases considered may differ from product to product according to the specific rules established. For this reason, we talk about life cycles "from cradle to gate", i.e. from the extraction of raw materials to the factory gate, or life cycles "from cradle to grave"), i.e. the entire life cycle up to the final disposal of the product.

Its contents are aimed mainly at industrial and commercial users of the product, taking full advantage of the peculiarities of business-to-business communication. Therefore, the Environmental Declaration must be transparent so that everyone can understand and interpret it correctly and, above all, be credible to avoid the phenomenon of green-washing [Passer, 2015].

There may be different types of EPDs on the market, of which the most widespread are:

1) Product EPD

- declaration relating to a specific product by a specific manufacturer;
- declaration relating to the average production of a product carried out in different plants by a specific manufacturer;
- statement regarding the average product among different products in a specific plant by a specific manufacturer;
- declaration regarding the average product among different products in different plants by a specific manufacturer;

2) Sector EPD

- declaration relating to the production of a specific product, as an average of the production carried out in different plants by different producers;
- declaration relating to the production of an average product, as an average of the production of different products carried out in different plants by different producers;

3) Product or sector EPD based on a qualified tool.

16.2 The content of an EPD

The fundamental rules necessary to draw up an EPD are contained in the ISO mentioned above 14025 standard, in ISO 14040 and ISO 14044 (specifically for the LCA study), and in the PCR (Product Category Rules) which, in the construction sector, is the EN 15804 standard " Sustainability of constructions - Environmental product declarations - Development framework rules by product category".

The following information must be included in an EPD [ISO 14025]:

a. identification and description of the organization making the declaration;
b. product Description;
c. product identification;
d. references to the Program Operator;
e. identification of PCRs – Product Category Rules;
f. publication date and validity period;
g. LCA - Life Cycle Assessment, LCI - Life Cycle Inventory data or information modules, including environmental impacts (for example consumption of resources, emissions into air, water, and soil, climate change, destruction of the stratospheric ozone layer, soil acidification and groundwater, eutrophication);
h. additional environmental information;
i. product content declaration covering materials and substances to be declared (for example, information regarding materials and substances that may have harmful effects on human health and/or the environment at all stages of the life cycle);
j. primary data and system boundaries: identification of the life cycle phases considered while highlighting those not declared;
k. statement that environmental statements from different programs may not be comparable;
l. information on places where it is possible to obtain explanatory materials;
m. information on who performed the EPD data verification.

Furthermore, to standardize the format of the Declarations, within the Eco Platform, an association that brings together the leading international Program Operators in the construction sector, the following sections are included, which contain various helpful information for the reader to immediately identify what is of interest and provide all quantified environmental information on the product:

1. Cover, where the logos will be positioned and the product will be immediately recognizable through a typical figure. Information will be provided regarding the name of the Organization, the Program Operator, and Eco-Platform, with the Eco EPD logo. Furthermore, the registration number and the dates of the EPD (issue, update, and expiry) must be entered.
2. General information relating to the Organization and the product (address of the factories, name of the product, its functionality). The reference PCR identification should be entered and the purpose of the EPD (cradle to gate, cradle to gate with options, or cradle to grave). The type of EPD (product EPD, sector, media...) and other general information;
3. Section C, dedicated exclusively to the description of the product covered by the EPD;
4. Section D, where the results of the LCA are described, and the environmental impacts are identified;
5. Section E, where the calculation rules adopted are described;
6. Section F, is dedicated to bibliographical references.

16.3 Third party verification and publication of the EPD

To be valid and acceptable by the market, the EPDs must be published on the website of the body (Program Operator), which establishes the verification criteria and publishes the rules so that the criterion of comparability of the environmental impacts of two products can be satisfied.

For the EPD to be published by a Program Operator, it is therefore necessary for the company to develop, independently or with the help of expert consultants, an LCA study report of the product or service and from this, obtain the environmental information to be reported on the EPD itself. Therefore, the EPD and the LCA must be subject to verification by an independent party, identified according to the requirements defined by the Program Operator itself. Once the independent party verifies the EPD, it is sent to the Program Operator, who publishes it in publicly consultable lists on the Program Operator's website. Some of these, such as the Italian Program Operator EPDItaly, have identified these subjects in the only certification bodies accredited to carry out these checks, thus providing their system with a high-level control method, guaranteed by the accreditation system.

The verification conducted by a third party has the essential task of guaranteeing the market that the principles of competence, independence, and impartiality have been adequately applied. The meticulous verification procedures by the third party are conducted under accreditation.

In order to promote the diffusion of the EPD, some Program Operators have developed specific tools to support the development and subsequent verification of LCA studies. In the EPDItaly system - for example - it is possible to find a method whose checks are conducted under accreditation, called the LCA tool. In essence, there is the possibility of developing different LCA studies of products to publish different EPDs, using the exact calculation modeling (algorithm). This involves optimizing the verification activities of each EPD, through a validation process of the algorithm used and the subsequent verification of its correct use for the specific EPD.

In fact, based on the same LCA model, the calculation algorithm allows the different impacts of the products to be determined as the input data varies. Verifying the corresponding EPDs is simplified as verifying the previously validated calculation model each time is unnecessary. The verification lets the user ascertain the tool's identification characteristics, completeness, correctness, appropriateness, security, and integrity.

Suppose the calculation algorithm is modified in the parts of code relating to the LCA model implemented, the types of products managed, or the boundaries of the system implemented. In that case, the algorithm itself must be revalidated.

Finally, it is also important to remember the existence of mutual recognition agreements between EPDItaly and various international Program Operators, which allow an EPD to be published both in Italy and abroad as long as it has been developed in compliance with the relevant international standards and requirements. This approach is permitted in the Eco Platform circuit and beyond, thanks to meticulous technical analyses of the characteristics of each program, so that the checks conducted by both can be considered equivalent.

16.4 'Comparability'

Using a particular format for EPDs and a standard format for construction products is an attempt to harmonize the different environmental product declarations to facilitate reading, interpretation, and comparison.

The concept of benchmarking has developed increasingly over the years. The need to compare products placed on the market and "representative" products has always been the subject of discussions and opinions, even more so when environmental impacts are declared.

The comparability of the EPDs of two products can be achieved with some requirements [ISO 14025]:

- same product, function, technical performance, and use);

- identical functional unit;
- equivalent system boundaries;
- equivalent data description;
- criteria for the inclusion of identical inputs and outputs;
- data quality requirements, including coverage, precision, completeness, representativeness, consistency, reproducibility, equivalent sources, and uncertainty;
- identical units of measurement;
- inventory analysis - equivalent data collection methodology;
- inventory analysis - identical calculation procedures;
- inventory analysis - equivalent allocation;
- the selection of impact categories and identical calculation rules;
- identical inventory data categories and impact category indicators.
- equivalent additional environmental information requirements;
- dangerous materials and substances to be declared equivalent;
- instructions are provided for producing the data required to develop the equivalent declaration.
- instructions on the content and format of the equivalent EPD.
- information on which phases are not considered equivalent;
- equivalent validity period.

16.5 Using an EPD

In recent times and in various fields, interest in EPD has increased.

Suffice it to say that, in the construction sector, there are several cases of diffusion policies, which represent an essential incentive for manufacturing companies that intend to differentiate themselves from competition that is less attentive to environmental issues while at the same time guaranteeing the market the sustainability characteristics of their products.

In the infrastructure sector, for example, the Envision voluntary certification system rewards using EPDs for the products making up the infrastructure [Božiček, Kunič, and Mitja, 2021] [Khasreen, 2009]

As regards the voluntary building certification systems, version 4 of Leed (Leadership in Energy and Environmental Design) has introduced, compared to the past, two new credits that enhance choices in the environmental field:

- Building Life Cycle Impact Reduction, which incorporates some pre-existing credits and encourages the evaluation of the complete life cycle of the building;
- Building Product Disclosure and Optimization – Environmental Product Declarations reward products with a better life cycle and an EPD.

In Italy, the Decree on Minimum Environmental Criteria (CAM) for construction, which requires the satisfaction of some criteria familiar to all building components: reduction of environmental impact, increase in the use of recycled materials, and waste recovery, requires the presentation to the Contracting Authority of appropriate documentation demonstrating compliance with the requirements mentioned above, and these documents include the EPD compliant with the EN 15804 standard, published for example on EPDItaly.

17 Appendix 2: Life Cycle Assessment and Green Procurement

17.1 The ongoing revision of the European Union's Construction Products Regulation

The current Construction Products Regulation (Regulation (EU) No 305/2011, Construction Products Regulation, CPR) applies in full from 1 July 2013. Its objective is to ensure the proper functioning of the internal market for construction products, thanks to harmonized standards that regulate their marketing in the European Union. The CPR, which defines a common technical taxonomy for assessing the performance of construction products, allows Member States to define regulatory requirements for the regulation of construction works. On 30 March 2022, the Commission presented a proposal to revise the CPR; The proposal is part of a package with several other sectoral proposals aimed at making sustainable products the norm in the EU and promoting circular business models. The stated objectives of the proposal are to improve the functioning of the internal market for construction products, address the (still ongoing) supply chain transformation challenges at the national level, simplify the legal framework, and support the green transition and digitalization in the sector. The regulation is expected to come into force between 2023 and 2024.

An innovative and essential component of the new regulatory model is that relating to environmental compliance requirements for producers. In the proposed new regulatory model, they would be required to assess the environmental characteristics (e.g. the effects of climate change) of construction products in line with the harmonized technical specifications or delegated acts adopted by the Commission under the regulation [Testa et al., 2016]. They should, essentially:

- design and manufacture the products and their packaging in such a way that their overall environmental sustainability, including emission sustainability for the purposes of containing the greenhouse effect, reaches the most advanced level;
- give preference to recyclable materials and materials obtained from recycling;
- comply with the obligations of the minimum content of recycled material and other limit values relating to environmental aspects, including climate sustainability, contained in the harmonized technical specifications;
- design products so that they can be easily repaired, refurbished and updated;
- make available instructions for use and information on how to regenerate or recycle the products and any additional information necessary for reuse, regeneration, or recycling.

The Commission would have the power to specify such obligations through delegated acts for particular families and categories of products. Alternatively, the Commission could issue standardization requests to develop harmonized regulations that provide a presumption of conformity to these obligations for a specific family or category of products. Such obligations would not apply before the entry into force of such delegated act or harmonized standard.

Considering that the final standard may undergo modifications, the intent to introduce a sustainability metric into the construction world's production system (in the factory and on-site) is clear [EU Green Procurement Toolkit, 2022].

There is wide research on the matter that has a global footprint. Bratt et al. (2013) set a general overview of green procurement criteria and methods, while Khairul, and Chamhuri (2012) describe green procurement practices in the Far East, Brammer and Walker (2011) and Carter and Fortune (2016) analyze the situation in the UK. Faith-Ell et al., (2006) present the Scandinavian and Swedish perspective and Montalban et al. (2016) analyze the Spanish context.

17.2 Buying sustainability

How the European Union, but also the overseas markets, look at the transformation of the construction supply chain is based on the instrument of environmental product declarations, through which (with greater or lesser determination, according to the type of regulation in force and the cultural and legal approach of the issuing country) is intended to provide a shared assessment of sustainability (in particular of the environmental and social pillars). This approach has succeeded in the construction world, where the range of products is more varied and 'factory' products have a more significant impact. Indeed, the world of infrastructures has an additional degree of complexity: the most significant products from an impact point of view still undergo many further on-site processes, which significantly modify their environmental performance, introducing elements of variability that differ from site to site and from one type of work to another [Sourani et al., 2011, 2013 and 2023].

This is why the LCA can allow a 'transparent' integration of EPDs (and environmental labeling, in general), making them the project's real EPDs (or environmental labels) through an additional integrated process evaluation calibrated on the site.

However, what happens once the environmental performance measurement has been made? What do we do with quantifying the GHGs emitted or evaluating the substances/incidences emitted for the other impact categories? Once we have demonstrated the best performance of a particular construction solution (and the related investments in research and innovation), how can we see it recognized? How do we translate this information into elements that can support the decision of a purchasing department or a customer?

17.2.1 First proposal

A possible cross-application of sustainability protocols and LCA has been illustrated in the previous pages. The contracting authority can request a sustainability assessment of this kind (sustainability indicators combined with supporting LCA analysis) on the critical infrastructure processes to be created, define a consequent assessment scale, and compare the contractors' proposals with each other or concerning a baseline. In this way, productions or technical solutions that reduce impacts could be rewarded, or 'laying and implementation' methodologies that, by leveraging localization, optimize environmental performance.

17.2.2 Second proposal

Considering in more detail an experience of the Norwegian Road Authority (and part of a strategy developed with the EPD-Norway body, which regulates the certification of product and process EPDs in Norway), it is possible to take a further step forward. In this case, the client estimates a reference baseline (concerning a hypothesis of helpful life and duration of the various construction and maintenance cycles) of the emission content of the road pavement subject to the tender through an LCA/EPD process analysis. At the tender stage, contractors are asked to improve the performance of this baseline, demonstrating the efficiencies achieved with their proposed process through a dedicated LCA calculation. For each kg of CO2eq obtained in reduction compared to the baseline, the contracting authority deducts €0.5/kg of CO2eq from the final price offered (approximately equal to the current value of the average carbon tax on European and American territory); naturally, it 'recharges' the price offered for each kg of CO2eq emitted in addition to the baseline. The evaluation concerning the baseline includes specific hypotheses with respect to all phases of the life cycle and for functional performance so that a 'reduced' offer on a specific phase is evaluated with a view to the overall duration of the useful life and of its effective compliance with the 'core' needs of the infrastructure. More 'technically sustainable' bidders see their equivalent offered price decrease and can win the tender 'on environmental merit' traced back to an equivalent economic evaluation.

This proposal has the advantage of engaging both the client and the supplier in a quantitative demonstration of the requests, on the one hand, and the offers, on the other, terms of reference consistent with the project requirements, measurable, calculable, and reproducible on site.

17.2.3 Involve the contracting authorities

Given the current stage of awareness regarding sustainability issues, the reference point for measurement or calculation must be clear and unambiguous. For example, we believe that focusing on GHGs (mainly CO2, CO2eq CH4, NOx) represents a practical first step, if only for the reason that there is trading around these emissions and that economic reference values for the estimate are starting to be defined of their socio-environmental impact (these are considerations that underlie the valorization of the carbon taxes of the countries that have applied them).

The construction sector, particularly the producers of the most significant materials from the point of view of their quantitative relevance and impact on the factory or construction site, can find in process LCA the ideal tool for communicating on a transparent and quantitative basis with their customers. In the same way, clients can stimulate the green supply-chain and make their work more easily financed by 'green' finance with the same LCA tool.

18 Appendix 3: Index of figures

19 Appendix 4: Index of tables