Management of excavated soil and rock

A literature review on mass management and circularity practices

LUCIJA PRSA GAZILJ

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF GEOLOGY AND GEOTECHNICS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

Management of excavated soil and rock
A literature review on mass management and circularity practices

LUCIJA PRSA GAZILJ

Department of Architecture and Civil Engineering
Division of Geology and Geotechnics
031 772 21 28, 070 366 29 92
prsa@chalmers.se

Chalmers University of Technology
412 96 Gothenburg, Sweden
www.chalmers.se

Summary

This literature review emphasizes the importance of effective mass management, with a specific focus on sustainable management of excavated soil and rock from construction projects. Excavated soil accounts for approximately 52% of the construction and demolition waste, and 20% of the total waste generated yearly in Europe. As urbanization continues to increase, with the global population expected to reach 9.7 billion by 2050, the environmental impact of the construction sector, especially its energy consumption and CO_2 emissions, remains a major concern. The review examines how frameworks such as Circular Economy, Urban Metabolism, and Doughnut Economy can provide solutions to these challenges and foster more sustainable practices in managing excavated soil.

The review's primary objective is to assess current mass management practices with a focus on sustainability and circularity, identifying strategies to improve the handling of excavated materials in a circular economy framework. It also delves into the regulatory frameworks and legislation that govern mass management. Key barriers to more effective mass management and increased reuse of soil and rock include regulatory inconsistencies, economic disincentives, and concerns over the quality of the excavated soil and rock. To overcome these challenges, the review recommends strengthening regulatory frameworks, integrating reuse into urban planning processes, and implementing digital systems that enhance resource coordination and management while enabling more effective tracking and documentation of excavated materials.

Case studies from countries such as the Netherlands, Belgium, and France demonstrate the success of innovative regulations and digital tools in advancing soil management practices. The examples illustrate the potential for collaborative efforts between industries and governments to improve mass management outcomes. Reusing excavated soil for applications such as base layers, recycled building materials, and other construction products can significantly reduce the reliance on virgin materials and contribute to greater sustainability. By addressing current barriers and implementing effective strategies, the sustainability of excavated soil management can be greatly enhanced, aligning with broader goals of sustainable urban development.

Despite these advances, a significant research gap remains in understanding how Circular Economy strategies should be clearly defined and effectively implemented in excavated soil and rock management. The review also shows that indicators and key performance indicators for measuring sustainability and circularity in ESR management are not yet widely or systematically applied. To address this gap, this PhD project will not only identify and develop relevant indicators and KPIs but will also contribute to creating a tool for measuring circularity and sustainability in ESR management. Together, these efforts aim to support more consistent assessment, monitoring, and continuous improvement of sustainable and circular mass management practices.

Acknowledgement

This literature review was produced as part of the “Indicators for Circular and Sustainable Mass Handling in Infrastructure Projects (INDIMASS)” research project with funding from the Swedish Transportation Agency (Trafikverket).

Content

Abbreviations

AMA	Allmän material och arbetsbeskrivning/ General Material and Work Description
BAU	Business-as-usual
CALCAS	Co-ordination Action for Innovation in Life Cycle Analysis for Sustainability
CBA	Cost-benefit Analysis
CDW	Construction and demolition waste
CE	Circular Economy
CEMs	Construction Excavation Materials
CV	Contingent Valuation
COP 15	Conference of the Parties
DALY	Disability-Adjusted Life Years
DE	Doughnut Economics
EC	European Commission
ELSA	Energiledningssystem för anläggningar/Energy Management Systems for Facilities
ESR	Excavated soil and rock
EU	European Union
EWC-Stat	European Waste Code-Statistics
FA	Farligt avfall/Hazardous waste
GHG	Greenhouse Gas Emissions
HPM	Hedonic Pricing Methods
IFA	Icke-farligt avfall/Non-hazardous waste
INDIMASS	Indicators for Circular and Sustainable Mass Handling in Infrastructure Projects
IS	Industrial Symbiosis
ISO	International Organization for Standardization
KM	Känslig Markanvändning/Sensitive Land Use
KPIs	Key Performance Indicators
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCSA	Life Cycle Sustainability Analysis
LOW	List of Waste
NbS	Nature-Based Solution
NPV	Net Present Value
MAUT	Multi-Attribute Utility Theory

MCDA	Multi-Criteria Decision Analysis
MDGs	Millennium Development Goals
MEFA	Material and Energy Flow Analysis
MFA	Material Flow Analysis
MFCA	Material Flow Cost Accounting
MRI	Midwest Research Institute
MKM	Mindre Känslig Markanvändnig/Less Sensitive Land Use
MRR	Mindre än Ringa Risk/Less than Negligible Risk
PSRV	Platsspecifikt Riktvärde/Site-Specific Guideline Value
RCAs	Recycled crushed aggregates
RP	Revealed Preference
SDGs	Sustainable Development Goals
SEPA	Swedish Environmental Protection Agency
SETAC	Society of Environmental Toxicology and Chemistry
SFA	Substance Flow Analysis
SP	Stated Preference
TrV	Trafikverket/Swedish Transport Administration
UM	Urban Metabolism
UN	United Nations
UNCBD	UN Convention on Biological Diversity
UNFCCC	UN Framework Convention on Climate Change
QALY	Quality-adjusted Life Years
WFD	Waste Framework Directive
WP	Work Package
WTA	Willingness to Accept
WTP	Willingness to pay

Glossary

Emerged masses	The term "emerged masses" refers to the soil and rock material that has been excavated or blasted for the specific purposes of a project.
Excavated soil and rock	Excavated material (e.g., clay, silt, sand, organic soils, and rock) generated during construction and infrastructure development projects, with characteristics that depend on the site-specific geological conditions.
Indicator	A measure that shows the state of something.
Key performance indicators (KPIs)	A measure used to evaluate the success of an organization, an employee, etc., in meeting objectives.
Masses	Materials extracted or displaced during excavation or blasting activities, typically in construction, infrastructure, or mining projects, include not only excavated soil but may also include crushed rock, torn asphalt, dredged materials, ash, slag, and other similar materials. *Note: _In this report, both the terms "excavated soil and rock" and "masses" are used, with the former being more commonly found in the reviewed literature. However, in Swedish literature, the term "masses" is used more frequently._
Needed masses	The needed masses represent the demand for soil and rock material during the specific project construction.
Surplus masses	Represent the excess soil and rock material that is excavated or left over during the project excavation.
Sustainable mass management	Sustainable mass management aims to avoid unnecessary generation of masses, and any masses that do arise should be used in a resource-efficient, socioeconomically beneficial, and environmentally sound manner, while also achieving good landscape adaptation.
Reutilized masses	Excavated materials diverted from waste disposal by using them in construction or infrastructure projects, typically for purposes like backfilling, landscaping, embankment creation, etc.

1 Introduction

1.1 Background

The 2024 Revision of World Population Prospects indicated that the global population is anticipated to grow from 8.2 billion in 2024 to 10.3 billion by the mid-2080s (United Nations Department of Economic and Social Affairs, 2024). Additionally, by 2050, the global population is projected to reach 9.7 billion, and 68% of these people are expected to live in urban areas (United Nations, 2019). This means that more than two-thirds of the world's population will be city dwellers by mid-century. However, the strain of growing urbanization is evident in its detrimental effects on the environment. Urban areas account for approximately 80% of global energy use (Grubler et al., 2012) and are also responsible for about 80% of worldwide CO_2 emissions (Heinonen & Junnila, 2011). Within these areas, the building and construction sector has emerged as a significant contributor to CO_2 emissions (Peters et al., 2007), as it is responsible for 32% of the emissions, as well as for 40% of the total energy consumption annually (van Eldik et al., 2020). Moreover, 50% of the finite natural resources in the world are used in infrastructure projects (UNEA, 2021). In 2019, construction and infrastructure utilized more than 100 billion tons of these resources (Larsson & Gammelsæter, 2023). In addition to all of the above, the construction industry in Europe is responsible for producing 25% of the yearly waste (van Eldik et al., 2020). The majority of this waste, by volume, comes from excavated masses, with a significant portion ending up in landfills (Eurostat, 2023).

As urbanization continues to rise, the need to address the environmental, economic, and social impacts of construction becomes increasingly critical. Frameworks such as Urban Metabolism (UM), the Circular Economy (CE), and the Doughnut Economy offer conceptualizations to better understand these challenges and to find solutions that support sustainable development. These industrial ecology frameworks utilize a variety of assessment tools, including Material Flow Analysis (MFA), Life Cycle Assessment (LCA), Cost-Benefit Analysis (CBA), and Multi-Criteria Decision Analysis (MCDA), to comprehensively evaluate sustainability impacts. As such, and even with uncertainties associated with data input, these tools can provide a more integrated understanding of how to optimize resource use, minimize waste, and foster long-term sustainability in construction.

One often overlooked issue is mass management. As previously noted, excavated masses from infrastructure projects are not properly managed, with the majority being sent to landfills, even though 80% of the excavated masses in Europe are uncontaminated (Eurostat, 2023; Frédéric, 2021). Significant amounts of masses are emerging during the construction, reconstruction, and maintenance of road and rail infrastructure, encompassing various materials as well as environmental and technical properties (Andersson-Sköld et al., 2022). In 2019, 4.2 billion tons of aggregates were used in Europe alone, of which only 7 percent was part of the CE (Larsson & Gammelsæter, 2023). Increasing circularity from 7 percent to 20 percent could save 6 billion euros annually by implementing measures like increasing reuse and reducing the extraction of natural resources from quarries (Larsson & Gammelsæter, 2023). However, legislation and today's infrastructure make the possibility of recycling these masses a complex question (Andersson-Sköld et al., 2022). In light of these challenges, adopting CE principles provides a structured approach to improving the management of excavated materials by promoting reuse, minimizing waste, and reducing dependence on primary resource extraction. (Larsson & Gammelsæter, 2023). In particular, reusing excavated soil offers several key benefits, including reduced transportation distances, lower disposal costs, preservation of landfill capacity, conservation of natural resources, and decreased environmental and ecological impacts (Walsh et al., 2019).

This literature review is part of a PhD research project titled “Indicators for Circular and Sustainable Mass Handling in Infrastructure Projects (INDIMASS).” The goal of the PhD project is to identify the most relevant indicators and key performance indicators (KPIs) to guide towards more circular and sustainable mass management, both at the level of individual projects and at the societal level. The project is funded by the Swedish Transport Administration (TrV), the major player in Sweden's infrastructure sector. The project builds upon the pre-study *"Mass Management – indicators and Key Performance Indicators for Reduced Climate Impact in Procurements"*, which highlighted the need for increased sustainability and clearer incentives for circular mass management. Additionally, it identified a lack of consensus on current mass management reporting within TrV projects and insufficient incentives for improving mass handling (Andersson-Sköld et al., 2022). Furthermore, as a result of the study, indicators and KPIs were proposed, and an Excel-based prototype was developed to report several of these indicators both before procurement and for use in monitoring and evaluating mass management within a project (Andersson-Sköld et al., 2022).

1.2 Aim and Specific Objectives

The purpose of this literature review is to thoroughly examine the current global conditions and practices surrounding the management of excavated soil and rock (ESR), with a particular emphasis on sustainability and circularity. It aims to identify effective methods for measuring the sustainability of ESR management and strategies for achieving circular mass handling. The findings from this review will serve as the basis for further research.

Specific objectives are to:

- Examine the existing literature on the management of ESR, considering legislative frameworks, digital advancements, current methodologies, and exemplary practices within mass management projects.
- Investigate and describe the general concepts of sustainability and circularity, focusing on how these are measured and evaluated within mass management projects using methods like MFA, LCA, CBA, MCDA, and other relevant approaches.
- Identify potential solutions suggested for achieving more sustainable and circular mass management practices.
- Investigate the use of indicators and KPIs as tools for assessing circularity and sustainable mass management practices.

1.3 Method

To address the stated aim and specific objectives, a comprehensive methodological approach was adopted, combining a scientific literature review, an examination of grey literature, and the collection of insights from relevant stakeholders. The review process was carried out during autumn 2024 and spring 2025. The scientific literature review was conducted using the Scopus database, applying a combination of structured search strings, citation tracking, and snowballing techniques (i.e., examining references in key publications). In parallel, grey literature was reviewed to capture practical, policy-oriented, and emerging perspectives not covered in peer-reviewed research. Relevant information was also gathered through an analysis of EU and Swedish legal frameworks. This included reviewing directives, regulations, national legislation, and policy documents to contextualize the research within the applicable regulatory environment. Additional insights and supporting materials were obtained through stakeholder consultations and workshop discussions.

1.4 Limitations

The study is subject to several limitations. The scientific literature review relied solely on the Scopus database, which may have excluded relevant studies elsewhere despite the use of structured search techniques. The inclusion of grey literature introduced variability in quality, transparency, and availability, potentially limiting the consistency and completeness of non-academic insights.

The legal and policy analysis was restricted to publicly available EU and Swedish documents, meaning internal or unpublished materials could not be considered, and ongoing policy developments may not be fully reflected. Stakeholder consultations provided valuable perspectives but were influenced by those who chose to participate, which may not represent the full range of stakeholder views. The review was also limited to literature available in Swedish and English, potentially excluding relevant research or policy documents published in other languages. Finally, the review was conducted during autumn 2024 and spring 2025, so more recent research or regulatory changes fall outside the study’s temporal scope.

2 Legislative and Policy Framework for Excavated Soil Management in the European Union

2.1 Waste Framework Directive

In 2008, the European Commission and Parliament introduced the Waste Framework Directive (WFD), which established basic concepts and definitions for waste management along with the waste hierarchy within the European Union (EU) (European Parliament and the Council, 2008). The waste hierarchy establishes the prioritization for waste management, detailing actions in the following order: prevention, preparation for reuse, recycling, recovery, and disposal (European Parliament and the Council, 2008), as illustrated in the Figure 2-1 below.

Figure 2-1. The waste hierarchy (European Union, 2022).

According to the definition provided by WFD (European Parliament and the Council, 2008) ***Prevention*** indicates measures taken before a substance, material, or product becomes waste, aimed at reducing:

- the quantity of waste, including through the reuse of products or extending their lifespan;
- the negative impacts of the generated waste on the environment and human health; or
- the presence of hazardous substances in materials and products.

Preparing for reuse involves checking, cleaning, or repairing products or components that have become waste, enabling them to be reused without further pre-processing (European Parliament and the Council, 2008). Reuse refers to the process of using these products or components again, for the same purpose they were originally designed, once they are no longer classified as waste (European Parliament and the Council, 2008). The key difference is that during the preparation for reuse, the product is still considered waste, whereas once it has been prepared and returned to the market, it ceases to be waste.

Recycling describes any recovery operation where waste materials are reprocessed into products, materials, or substances, either for their original purpose or for other uses. This includes the reprocessing of organic material but excludes energy recovery and the reprocessing of materials intended for use as fuels or in backfilling operations (European Parliament and the Council, 2008).

Recovery indicates any operation where the primary outcome is that waste serves a useful purpose, either by replacing other materials that would otherwise be used for a specific function, or by being prepared to fulfill that function, within a plant or the broader economy (European Parliament and the Council, 2008).

Waste management should be conducted in a manner that ensures no harm to human health or the environment. It must pose no risk to water, air, soil, plants, or animals. Furthermore, waste management practices should not create disturbances through noise or odors and must be managed without adversely affecting the countryside or areas of special interest (European Union, 2022).

Moreover, the WFD outlines specific criteria that determine when waste ceases to be classified as waste and is considered a product or secondary raw material, known as the *"end of waste"* criteria (European Parliament and the Council, 2008). To meet these criteria, the waste must undergo a recovery operation (as defined above) and satisfy certain conditions, including:

- The substance or object is regularly used for particular purposes.
- A market or demand exists for the substance or object.
- The use is lawful, meaning the substance or object meets the technical requirements for its intended use and complies with relevant legislation and product standards.
- The use does not result in negative environmental or human health impacts (European Parliament and the Council, 2008).

Additionally, the WFD provides definitions for various waste categories, including Municipal waste, Construction and demolition waste (CDW), Waste oils, and Biowaste (European Parliament and the Council, 2008). A detailed list of waste types is provided in the Commission Decision on the European List of Waste (European Commission, 2000). Since the excavated soils may be classified as CDW, this category is described in detail below.

2.1.1 Construction and demolition waste

Construction and demolition waste (CDW) comprises all waste generated by building and infrastructure construction and demolition, along with road construction and maintenance. This waste primarily includes materials such as concrete, bricks, wood, glass, metals, and plastic (European Commission, n.d.). However, EU countries use various definitions for CDW (European Commission, n.d.), leading to inconsistencies such as the inclusion (Blengini & Garbarino, 2010) or exclusion of ESR (Hiete et al., 2011). Under the Commission Decision on the European List of Waste (LoW), which serves as the waste classification system in the EU for administrative purposes (European Commission: Joint Research Centre: Cristóbal García et al., 2023), excavated soils are categorized as CDW waste (European Commission, 2000). It is marked with the two-digit code 17 for CDW, and the classification of the four-digit chapter headings is provided in the Table 2-1 below. For the complete definition of CDW with a six-digit code for the waste, please refer to the LoW (European Commission, 2000).

Table 2-1. Construction and demolition waste (CDW) classification (European Commission, 2000)

17	***Construction and demolition waste (Including excavated soil from contaminated sites)***
17 01	Concrete, bricks, tiles, and ceramics
17 02	Wood, glass, and plastic
17 03	Bituminous mixtures, coal tar, and tarred products
17 04	Metals (including their alloys)
17 05	**Soil** (including excavated soil from contaminated sites), stones, and dredging spoil
17 06	Insulation materials and asbestos-containing construction materials
17 08	Gypsum-based construction material
17 09	Other construction and demolition wastes

In the EU, alongside the LoW, there is also the European Waste Code- Statistics (EWC-Stat), which provides a substance-oriented aggregation of the waste types defined in the LoW (European Commission: Joint Research Centre, 2023). The study by (European Commission: Joint Research Centre, 2023) outlines various CDW fractions concerning the LoW and EWC-Stat. In Table 2-2 below, soils are categorized as CDW fractions.

Table 2-2. Description of the CDW fractions correlated with the LoW and the EWC-stat codes, from (European Commission: Joint Research Centre, 2023).

CDW fractions	**Considered in the study by (European Commission: Joint Research Centre, 2023)**	**LoW code**	**EWC-stat**
Mineral waste	Mineral waste	17 01	W12.1
Concrete	Concrete	17 01 01	W12.11
Bricks	Bricks	17 01 02	W12.11
Tiles and ceramics	Tiles and ceramics	17 01 03	W12.11
Other materials from road demolition	EXLUDED		
Mixed/other mineral/inert waste	Mixed/other mineral/inert waste	17 01 07	W12.11
Asphalt waste	Bituminous mixtures containing coal tar	17 03 02	W12.12
Plastic	Plastic	17 02 03 / 19 12 04	W07.42
Metal	Metal	17 04	W06
Mixed metals, incl. cables	Mixed metals	17 04 07, 17 04 11	W06.32, W06.26
Ferrous	Ferrous	17 04 05 / 19 12 02	W06.11
Non-ferrous	Non-ferrous	17 04 01, 17 04 02, 17 04 03, 17 04 04, 17 04 06 / 19 12 03	W06.24, W06.23, W06.25, W06.26
Glass	Glass	17 02 02 / 19 12 05	W07.12
Wood	Wood	17 02 01 / 19 12 07	W07.53
Gypsum	Gypsum	17 08 02	W12.11
Insulation	Insulation	17 06 04	W12.13
Paper and cardboard	Paper and cardboard	NA, 19 12 01	W07.23

Mixed waste, generic	Mixed waste, generic	17 09 04 / 19 12 09	W12.13 / W12.81
Mix of non-hazardous, non-inert wastes			
Mix of inert and non-hazardous, non-inert wastes			
Others			
Soils			
Unpolluted	Soils and stones	17 05 04	W12.61
Polluted	Soils and stones	17 05 03	W12.61
Dredging spoil			
Unpolluted	Dredging spoils	17 05 06	W12.71
Polluted	Dredging spoils containing dangerous substances	17 05 05	W12.71
Track ballast			
Unpolluted	Track ballast	17 05 08	W12.11
Polluted	Track ballast containing dangerous substances	17 05 07	W12.11
Hazardous waste (excl. hazardous soil, dredging spoil, track ballast)	Hazardous waste (excluding hazardous soil and dredging spoil)	17 01 06*, 17 02 04*, 17 03 01*, 17 03 03*, 17 04 09*, 17 04 10*, 17 06 01*, 17 06 03*, 17 06 05*, 17 08 01*, 17 09 01*, 17 09 02*, 17 09 03*	W12.11, W12.12, W10.22, W12.13, W12.21, W07.73

*Any waste marked with an asterisk (*) in the list of waste shall be considered as hazardous waste.

Furthermore, (Magnusson et al., 2015) reviewed the available literature concerning the management of ESR. They noted that the available literature concerning the management of CDW is generally uncertain due to illegal dumping activities and the lack of proper measurement at CDW facilities. Additionally, they stated that uncertainties are even larger when it comes to the fact that the definition of CDW varies. The varying definitions complicate cross-country comparisons regarding the level of recycling and material recovery of CDW (Cristóbal et al., 2024; European Commission, n.d.). In Europe, the level of recycling and material recovery of CDW varies significantly across the EU, ranging from less than 10% to over 90% (European Commission, n.d. ; European Commission: Joint Research Centre: Cristóbal García et al., 2023). The analysis by (Chen et al., 2012) of several recycling projects aimed to define recycling boundaries for different waste types. Their findings suggest that CDW is more suitable for recycling and recovery at the city level due to its low market value and high transportation costs.

Additionally, the objectives for CDW under WFD indicate that the EU plans to manage CDW in an environmentally sound manner and utilize its full potential to facilitate the transition to a CE. Concerning this, the EU protocol for CDW was published in 2016, in part to encourage a more circular utilization of materials (European Commission, 2016a). Despite the significant volume of ESR in Europe, which accounted for over 400 million tons in 2020 (European Commission: Directorate-General for Environment: Flexman et al., 2024; European Commission: Joint Research Centre: Cristóbal García et al., 2023), these materials were excluded from the protocol.

2.2 Landfill Directive

The Directive 1999/31/EC on the landfilling of waste, issued by the Council of the European Union in 1999, aimed to minimize any negative impact from landfills on surface water, groundwater, soil, air, or human health by introducing stringent technical requirements (Council of the European Union, 1999). The Directive outlines several key points, including the classification of landfills into three categories: hazardous waste landfills, non-hazardous waste landfills, and inert waste landfills (which contain materials that do not decompose or burn, such as gravel, sand, and stone) (Council of the European Union, 1999). Furthermore, in 2020, Directive 2018/850, which amends the Landfill Directive, came into force to support the European Union's transition to a CE (European Commission, n.d.-a). This Directive imposes restrictions on the landfilling of waste suitable for recycling or other material or energy recovery starting from 2030. Furthermore, it limits the share of municipal waste landfilled to 10% by 2035 (European Commission, n.d.-a).

2.3 European Soil strategy for 2030 and proposed Soil Monitoring Law

The EU Soil Strategy for 2030 outlines the framework and specific actions for soil protection, restoration, and sustainable use. Its vision is for all soils to be in a healthy state, i.e., they are in good chemical, biological, and physical condition by 2050. Among other measures, the Strategy includes specific actions aimed at ensuring the safe, sustainable, and circular use of excavated soil (European Commission, 2021). Specifically, the Commission plans to:

- Examine the excavated soils generated, treated, and reused in the EU, and compare the market situations in Member States by 2023 to provide a comprehensive overview of the EU landscape (European Commission, 2021).
- As part of developing the Soil Health Law/Soil Monitoring Law (see later in the text), assess the need and potential for implementing legally binding provisions for a ‘passport for excavated soil’, and provide guidance, based on Member States' experiences, to establish such a system. The passport should indicate the quantity and quality of the excavated soil to ensure safe transportation, treatment, or reuse elsewhere (European Commission, 2021).

In relation to these actions, the report “*Excavated Soil Generation, treatment and reuse in the EU”* (European Commission: Directorate-General for Environment: Flexman et al., 2024) provides an overview of current practices related to the reuse and disposal of excavated soils across EU Member States, analyzing the economic factors that influence soil management and identifying opportunities for more sustainable management of excavated soils. As previously mentioned, over 400 million tons of soil waste were generated in the EU in 2020, with 99% classified as non-hazardous (European Commission: Directorate-General for Environment: Flexman et al., 2024). In terms of soil waste generation by sectors in the EU, the construction sector generated the largest volume of soil waste, accounting for 95% (European Commission: Directorate-General for Environment: Flexman et al., 2024). The distribution of this waste across EU countries and member states is depicted in Figure 2-2 below.

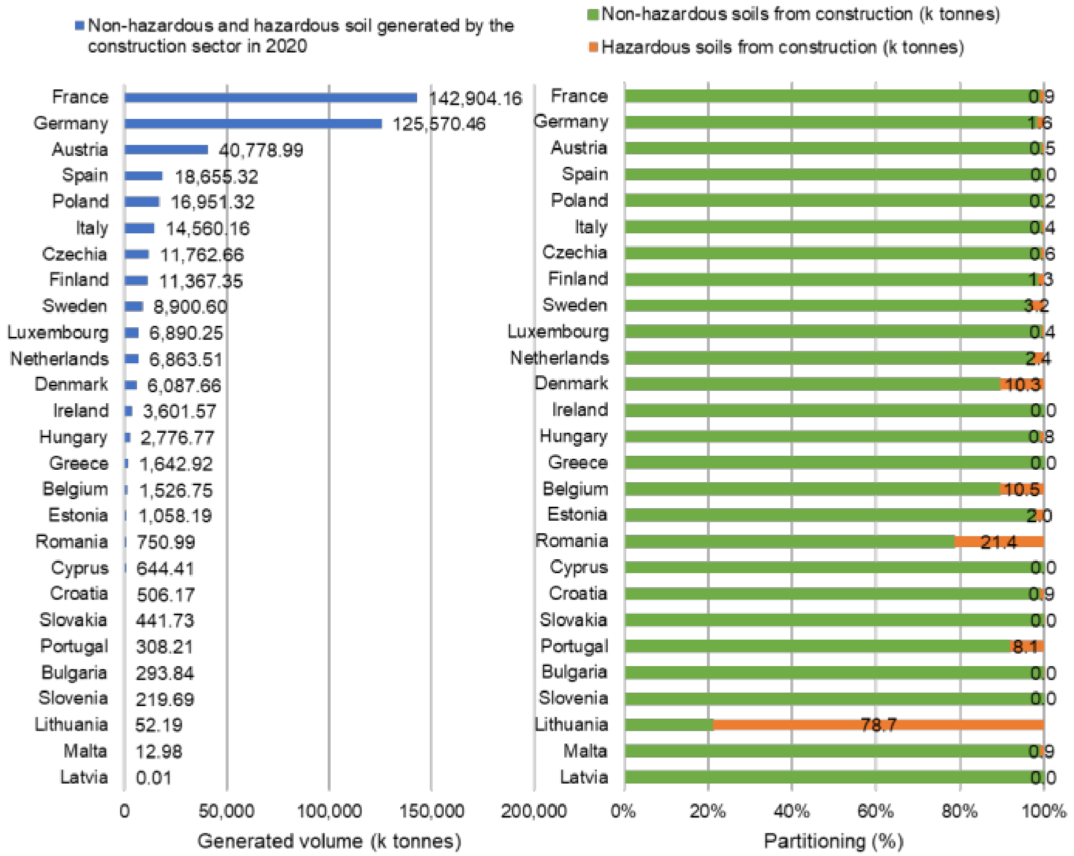


Figure 2-2. Total non-hazardous and hazardous waste soils generated in 2020 by the construction sector, from (European Commission: Directorate-General for Environment: Flexman et al., 2024).

According to the data above, France and Germany were the leading producers of soil waste in the construction industry, while Latvia and Malta saw a smaller contribution from the construction sector. Sweden ranked among the top 10 countries for construction-related soil waste, generating 8,900.60 K tons in 2020 (European Commission: Directorate-General for Environment: Flexman et al., 2024). In relation to soil waste generation per capita from construction, Luxembourg leads with the highest amount at 10.9 kg per person, followed by Austria at 4.6 kg per person, France at 2.1 kg per person, and Finland at 2 kg per person (European Commission: Directorate-General for Environment: Flexman et al., 2024).

In 2020, the EU reached a 75% recovery rate for soil waste, with 35% recycled and 40% used for backfilling, which is considered a lower-grade recovery process. The remaining 25% of soil waste was sent to landfills, while less than 0.02% was incinerated or used for energy recovery (European Commission: Directorate-General for Environment: Flexman et al., 2024; European Commission: Joint Research Centre: Cristóbal García et al., 2023). Further details are provided in Section 4.5.

In October 2022, the Soil and Land research funding platform for Europe, SOILveR, conducted a questionnaire on Soil Certificates and Soil Passports. Members (researchers, policymakers, and practitioners) of the platform provided their insights on the use of soil passports and certificates, contributing to the advancement of knowledge towards the EU Soil Strategy and Law, see Table 2-3 (SOILveR, 2022a).

The UK also participated in the questionnaire by providing a link to its main strategy: DoW:CoP, which is discussed in detail later in Subsection 2.5.6.

Table 2-3. Responses to the questionnaire on Soil Certificates and Soil Passports, based on (SOILveR, 2022a).

Country	Soil Passports Used	Soil Certificate System	Regulations
Flanders (Belgium)	Yes	Yes	Strict regulations govern excavated soil, focusing on volume, contamination, and traceability, with certified experts ensuring compliance. Flanders has required a mandatory soil certificate since 1995 for land transfers, detailing contamination, risk activities, and land use recommendations, ensuring site remediation before transfer. A soil certificate can be requested online from OVAM by anyone, for a fee of 55 euros.
Switzerland	No	No	-
Catalunya (Spain)	No	No	When a site is declared contaminated, the condition is recorded as a marginal note on the property's registration, but it does not include soil quality information.
Denmark	No	No	In Denmark, soil analysis is required for urban and contaminated land, managed by municipalities. However, only contaminated sites must be registered, with no general soil certification required, focusing mainly on contamination.
Slovak Republic	No	No	The Slovak Republic does not have an established system to monitor the process from soil excavation to its reuse. No specific passport system, uncontaminated soils might be exempt.
Austria	No (equivalent system exists)	No	Austria lacks a formal soil certificate system but uses an inventory of historical pollution and a national environmental status standard to assess land contamination, including standardized sampling and analysis for recycling, reclaiming, or landfilling based on soil quality.
Czech Republic	No (waste law applies)	No	Soil testing is required for organic and metal contamination. A risk assessment is needed if moving more than 1,000 tons. New decrees with stricter contamination limits.
France	No	No	France has a national traceability system for excavated soils, often paired with TERRASS for tracking reuse and recycling. While it lacks a traditional soil certificate, it uses Soil Information Sectors to identify contaminated areas and requires certificates like ATTES-ALUR for construction permits on these sites.
The Netherlands	No *The soil passport is introduced later, as detailed in Subsection 2.5.1	No	Environmental Declaration of Soil Quality is required for reuse, ensuring standards based on contamination and risks. The national register tracks the quality, quantity, and origin of excavated soils. There is no formal soil certificate system, but it relies on exchanging available contamination information during land transfers. Additional soil testing is voluntary and carried out by certified companies

Sweden	No	No	Sweden has a national registry of contaminated sites and follows a "polluter pays" and "caveat emptor" system, where the seller must disclose contamination, and the buyer is responsible for further investigation. Regional and local systems for reused soil traceability are suggested, with SEPA recommending waiting for the EU's soil passport initiative to assess its impact.

Sections 2.4 and 2.5 provide a detailed overview of the legislative and regulatory framework governing the management of excavated soil, with consideration given to several of the countries discussed above.

Additionally, in November 2022, the SOILveR webinar on Soil Certificates and Soil Passports was held, where the results of the questionnaire were discussed. It was concluded that most countries have systems under the waste regime to manage soil contamination during excavation and movement, with some having legal frameworks for excavated soil that go beyond waste regulations. Only one country uses a "soil passport" system and the term "soil certificate." While many countries see room for improvement, most support the adoption of a soil passport system or traceability systems (European Commission: Directorate-General for Environment: Flexman et al., 2024; SOILveR, 2022b). However, concerns were raised regarding varying pollution standards across EU Member States, potential misuse of the tool, and a lack of laboratory capacity in some countries. As a result, the proposal for mandatory soil passports was removed to ensure coherence with existing regulations under the WFD and to avoid administrative burdens (European Commission: Directorate-General for Environment: Flexman et al., 2024).

Furthermore, the Strategy also highlights the importance of reusing the excavated soil, as it is predominantly clean, fertile, and healthy. Additionally, it suggests that when reusing the excavated soil is not feasible, priority should be given to recycling or alternative recovery methods over landfilling, following the waste hierarchy (European Commission, 2021).

As part of the Strategy, a new Soil Monitoring Law has been proposed to standardize practices and enhance environmental and health protection, thereby helping to achieve healthy soils by 2050 (European Commission, n.d.-b). This would be done by:

- Establish a comprehensive and cohesive monitoring system for all soils across the EU, enabling Member States to take action to restore degraded soils.
- Promote sustainable soil management as the standard practice within the EU. Member States will be required to define and implement practices that soil managers must follow, as well as identify and ban those that lead to soil degradation.
- Instruct Member States to identify potentially contaminated sites, investigate these locations, and address any unacceptable risks to human health and the environment, thereby contributing to a toxic-free environment by 2050 (European Commission, n.d.-b).

In July 2023, the proposed Soil Monitoring Law was accepted by the Commission (European Commission, n.d.-b) and entered into force on 16 December 2025 (European Commission, n.d.-c).

2.4 National Legislative and Regulatory Framework for Excavated Soil Management in Sweden

The primary legal framework for managing soil and excavation masses and addressing land-related questions in Sweden is the Swedish Environmental Code, referred to as Miljöbalk (SFS 1998:808). In addition to this, several other legislative frameworks concurrently govern the management of CDW. The Environmental Code provides general rules for waste management, while the Planning and Building Act (Plan- och bygglag (2010:900)) includes additional provisions specifically related to waste generated by construction and demolition activities. Furthermore, the Waste Ordinance (Avfallsförordning (2020:614)) and its associated regulations offer more detailed guidelines for managing specific types of waste (Swedish EPA, 2024b).

According to the definition of waste as "all objects or material that the project owner wants to dispose of or has to dispose of" stated by the Environmental Code, the Swedish Environmental Protection Agency (SEPA) has proposed how this definition can be applied to masses, shown in Figure 2-3.

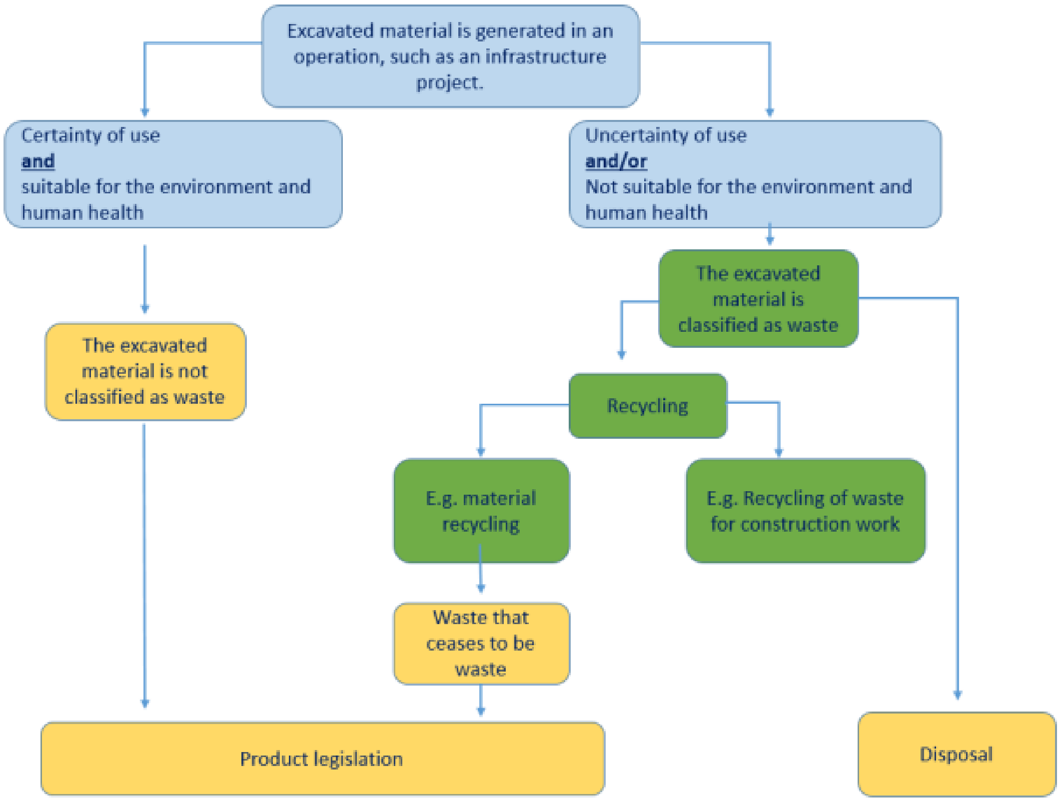


Figure 2-3. The SEPA suggested how the waste legislation should be interpreted for excavated material (Swedish EPA, 2023a). Translation based on (Andersson & Borre, 2024).

According to SEPA, excavated material is classified as waste if the owner cannot ensure that the material is suitable for both environmental and human health purposes, and if there is no confirmed certainty of use for the material. On the contrary, to verify that the material is considered a resource rather than waste, the owner must provide technical and environmental quality information about the material, demonstrating its suitability for the intended purpose at the specific location. However, the final responsibility lies with the material receiver regarding the material's suitability.

When the material can be used in another project, the owner must confirm its suitability based on technical and environmental standards. The material may then be sold on the current market if there is demand within the specified timeframe. If demand is assessed, a written contract to confirm material usage is not required.

Additionally, when determining whether material is classified as waste, it is essential to recognize that certain materials can be recycled and reused in construction. In such cases, obtaining the necessary permits is required. If no alternative solutions are feasible, the ultimate disposal of the material is at a landfill.

2.4.1 Material classification

In Sweden, the material classification is based on the technical and environmental characteristics, determining the potential for reuse. Examples of technical properties include particle size, deformation properties, and bearing capacity. Environmental properties encompass the presence of pollutants, total concentration, and leachability, as well as the maximum allowable values for specific projects. Systems to categorize and classify material based on technical and environmental properties are described further below.

2.4.1.1 Technical properties of the material

Technical descriptions for construction and installation works in Sweden are classified according to AMA (Allmän material- och arbetsbeskrivning), which stands for General Material and Work Specifications (Svensk Byggtjänst, 2023). This reference document is utilized in civil engineering projects and outlines the requirements for methods, technologies, and materials. AMA Construction 23 pertains to the classification of the technical properties of materials, as well as the work instructions (Svensk Byggtjänst, 2023).

Table 2-4 AMA CE/1 lists different materials in construction, classified by the percentage of fine soil, clay, and organic soil (classes 1-6B). Table 2-4 CE/2 in AMA Construction 2023 specifies filling materials for vegetated areas, categorized by material size (types 11-15) (Svensk Byggtjänst, 2023).

Table 2-4. Material types and descriptions from the tables AMA CE/1 and AMA CE/2, together with examples of construction codes (Svensk Byggtjänst, 2023). Translated by (Jansson & Olsson, 2024).

Material type	Name of soil and rock material	Example	Example of construction code & description
1	Rock type A	Mica-poor granite or gneiss and other hard and strong rocks such as quartzite, dolerite, porphyry, and leptite	CEB.111 Filling with blasted rock for roads, plans, etc.
	Rock type B	Mica-rich granite or gneiss and other rocks with moderate strength and poor wear resistance	CEB.53 Filling against the foundation
2	Boulder and stony soils Coarse-grained soils	Boulder, rock, gravel, sand, sandy gravel, gravely sand, gravel till, sand till	CEB.212 Filling with aggregate for building foundations

3A	Rock type C	Rocks with high mica levels, clay shale, some coarse-grained granites, and some porous sedimentary rocks, very strong transformed rocks	CEB.111 Filling with blasted rock for roads, plans, etc. CEB.82 Backfill against light materials
3B	Mixed-grain soils	Clayey or silty sand, clayey or silty gravel, clayey or silty sandy till, clayey or silty gravel till, clayey or silty till	CEB.82 Backfill against light materials CEC.3111 Filling around water and sewer lines
	Rock type D	Rocks with high mica levels, clay shale, chalk limestone, clay-converted rock, and not classified rock material	
4A	Mixed-grain soils	Rocks with high mica levels, clay shale, chalk limestone, clay-converted rock, and not classified rock material	CEB.214 Filling with mixed or fine-grained soil for building foundations CEC.3111 Filling around water and sewer lines
4B	Fine-grained soils	Clay, clay till	CEB.214 Filling with mixed or fine-grained soil for building foundations CEC.3111 Filling around water and sewer lines
5A	Fine-grained soils	Silt, muddy silt, silty clay, silt till, silty clay till	CEB.322 Filling with mixed and fine-grained soil for railways
5B	Mineral soils with organic content	Muddy clay, muddy silt	CEB.11222 Category B filling with mixed and fine-grained soil for road plan, etc.
6A	Organic, mineral soils	Clayey mud, silty mud, sandy humus soil	There are no construction codes for this material type
6B	Organic soils	Mud, peat, humus soil	There are no construction codes for this material type
11	Rock material	Blasted rock, gravel	CEB.121 Filling with blasted rock for vegetation surface
12a	Stone till, coarse and mixed-grained till Coarse soil Particle size > 2 mm	Clay-free or clay-poor gravelly soil, sandy gravel till	CEB.122 Filling with soil material for vegetation surface

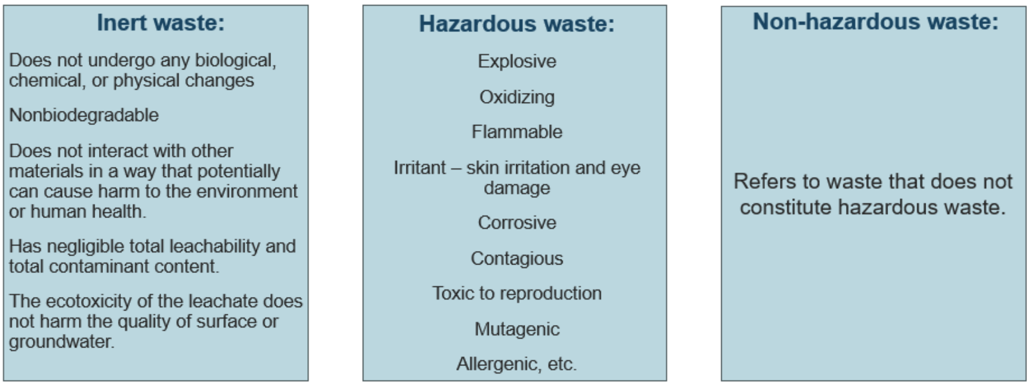
12b	Stone till, coarse and mixed-grained till Coarse soil Particle size < 2 mm	Clay-free or low-clay sandy soil, gravelly sandy till	CEB.122 Filling with soil material for vegetation surface
13a	Fine and mixed grain till Fine soil Particle size > 0.02 mm	Gravelly or sandy silt soils, loamy gravel, sandy or sandy soils, silty or loamy sand till	CEB.122 Filling with soil material for vegetation surface
13b	Fine and mixed grain till Fine soil Particle size < 0.02 mm	Clayey silt soil, light clay, clayey silt till	CEB.122 Filling with soil material for vegetation surface
14a	Fine-grained till, fine soil with dry crust character, particle size > 0.002 mm	Medium clay, clay till	CEB.122 Filling with soil material for vegetation surface
14b	Fine-grained till, fine soil with dry crust character, particle size < 0.002 mm	Stiff clay and very stiff clay, clay till	CEB.122 Filling with soil material for vegetation surface
15	Fine soil without a dry crust character	Medium clay, stiff clay, and very stiff clay	There are no construction codes for this material type

2.4.1.2 Environmental properties of the material

The environmental characteristics of the material are commonly assessed by two different methods: 1) measuring the total concentration of contaminants, including metals and organic substances, and 2) testing the leachability properties of the material (Swedish EPA, 2022b). SEPA has developed a model to establish guideline values for contaminated soil for several contaminants. These proposed guideline values determine the level of protection against health and environmental effects based on land use classification into sensitive (Känslig markanvändning-KM) and less sensitive (Mindre känslig markanvändnig-MKM) categories (Swedish EPA, 2022b). Examples of less sensitive land uses include industry, offices, and roads, while sensitive land uses include residential areas and playgrounds. These guidelines, developed to evaluate risks to human health or the environment at contaminated sites, are typically based on the total contaminant concentration and applied when evaluating the suitability of materials for disposal or reuse in construction projects (Swedish EPA, 2022b). Moreover, if there is no threat to human health or the environment, the material is classified as less than negligible risk (MRR) (Swedish EPA, 2010).

For material reuse in construction projects, local or regional regulatory authorities will determine the permissible contaminant levels based on the project's size and environmental impact (Swedish EPA, 2022a).

Additionally, the leachability test suggests the potential for contaminant dispersion (Elert et al., 2006). The leachability level of the material determines its classification as inert, non-hazardous, or hazardous for disposal purposes (Elert et al., 2006). The figure below presents some properties of inert, non-hazardous, and hazardous materials (European Parliament and the Council, 2008).



Inert waste:

Does not undergo any biological, chemical, or physical changes

Nonbiodegradable

Does not interact with other materials in a way that potentially can cause harm to the environment or human health.

Has negligible total leachability and total contaminant content.

The ecotoxicity of the leachate does not harm the quality of surface or groundwater.

Hazardous waste:

Explosive

Oxidizing

Flammable

Irritant – skin irritation and eye damage

Corrosive

Contagious

Toxic to reproduction

Mutagenic

Allergenic, etc.

Non-hazardous waste:

Refers to waste that does not constitute hazardous waste.

Figure 2-4. Characterization of the material according to leachability properties (after (European Parliament and the Council, 2008).

2.4.1.3 Classification based on mass suitability for the specific site

To ensure a uniform and sustainable approach to mass management in infrastructure projects, the TrV has established requirements for classifying excavated masses, focusing on the systematic methodology for sampling, analyzing, and evaluating these masses, starting from the initial planning stages through the realization and maintenance of infrastructure projects (Rossander, 2022). In addition to evaluating contamination levels in emerging masses excavated in road/infrastructure projects, it is necessary to assess the suitability of sites for these masses (Rossander, 2022). Table 2-5 below categorizes the land areas and provides examples and descriptions. The risk of contaminants spreading through the water body, groundwater, or surface water determines the size of the area. A1 indicates a permeable top layer, while A2 indicates an impermeable top layer (Rossander, 2022). Human exposure time describes the exposure concerning long-term effects, short-term exposure, acute toxicity from ingesting soil, skin contact with soil, and inhalation of dust and vapor (Rossander, 2022).

Table 2-5. Description and examples of land area L1, L2, S1, and S2 (Rossander, 2022) Translated by (Jansson & Olsson, 2024).

Type of site		**Top layer**	**Human exposure time**	**Example of land use or activity within the site**
L1	Small area, <500 m^2	Permeable surface	Limited exposure time, around 2 hours per day for children and adults, or around 30 days per year for children and adults.	The permeable part of a roundabout, road embankment, road area (inner and outer slopes, and any shoulder strip 0.5-2m outside the crest edge), smaller excavations, foundation replacements, sewerage, or smaller permeable surfaces.
L2	Small area, <500 m^2	Impermeable surface, no protection of the land environment	Limited exposure time, around 2 hours per day for children and adults, or around 30 days per year for children and adults. Low exposure to masses due to the impermeable surface.	Bus stop, passing pocket, or another smaller impermeable surface.

S1	Large area, >500 m^2	Permeable Surface	Moderate exposure time, around 3 hours per day for children and adults, or around 45 days per year for children and adults.	Railway, marshaling yard, embankments, embankment widening, service roads, gravel roads, road area (inner and outer slopes, and any shoulder strip 0.5-2m outside the crest edge), noise barriers, or other larger permeable surfaces.
S2	Large area, >500 m^2	Impermeable surface, no protection of the land environment	Limited exposure time, around 2 hours per day for children and adults, or around 30 days per year for children and adults. Low exposure to masses due to the impermeable surface.	Road, pedestrian and bicycle path, platform, or another larger impermeable surface.

2.4.2 Actors and functions in Swedish Mass Management

The mass management in infrastructure projects can be seen as a complex system involving multiple actors and functions operating across different governance levels (Eriksson et al., 2025). In the Swedish context, a distinction is made between functions (planning authority, supervisory authority, developer/client) and actors (public authorities and private sector organizations), see Figure 2-5, highlighting that many actors simultaneously perform several roles (Eriksson et al., 2025). This multiplicity contributes to fragmented decision-making and challenges for circular mass management (Eriksson et al., 2025).

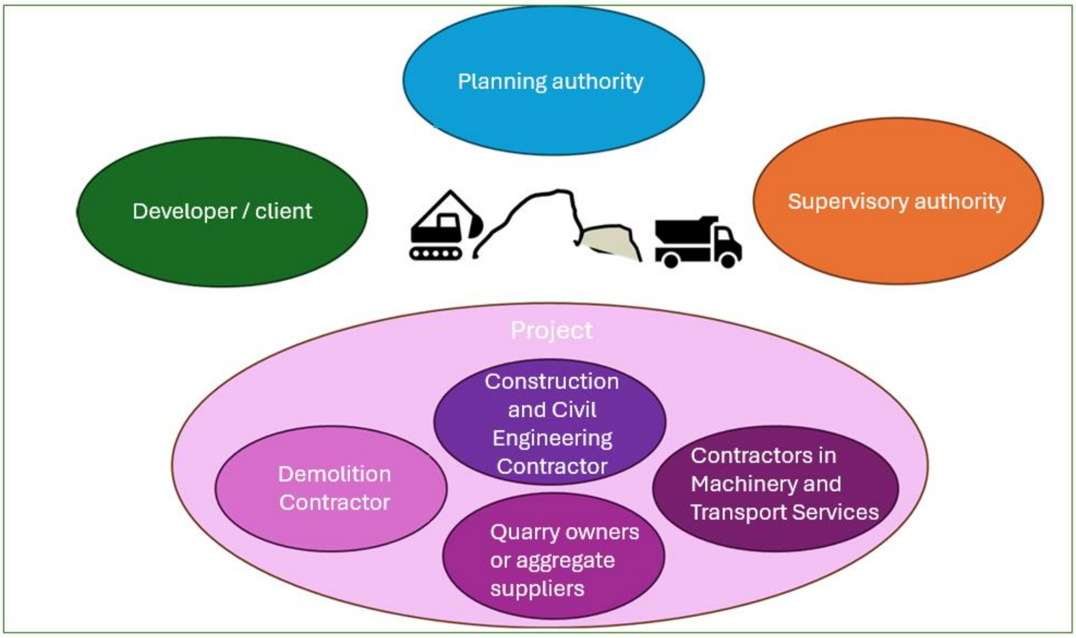


Figure 2-5. Different functions within the mass management system, from (Eriksson et al., 2025). Translated by the author.

Municipalities (Kommunen) play a central role through three main functions: planning authority, supervisory authority under the Environmental Code, and developer/client. As planners, municipalities regulate land use through comprehensive plans, detailed development plans, and building permits. These processes primarily focus on the final built environment rather than activities during construction, which often makes temporary mass storage and circular use of excavated materials invisible or unsupported in planning. As supervisory authorities, municipalities focus on environmental and health protection, especially contamination risks and waste classification, rather than material quality or reuse potential. As developers/clients, municipalities generate large mass flows through public infrastructure projects and therefore have significant, but not always fully utilized, leverage to influence practices (Eriksson et al., 2025).

County Administrative Boards (Länsstyrelsen) function mainly as supervisory authorities for environmentally hazardous activities and as coordinators of regional interests. While mass management is relevant across several of their mandate areas, it is predominantly handled from an environmental protection perspective. However, the boards also act as important hubs for coordination among municipalities, state agencies, and private actors (Eriksson et al., 2025).

The Swedish Transport Administration (Trafikverket) has dual roles as planning authority and developer/client and is Sweden's largest infrastructure developer. Mass management is particularly relevant in large infrastructure investments, yet it is often considered late in the planning process. Although mass balance assessments are conducted, they rarely have a decisive influence on corridor or alignment choices (Eriksson et al., 2025).

At the operational level, mass flows are organized by contractors, demolition firms, machine and transport operators, and quarry owners/material suppliers. These actors frequently operate in overlapping roles and rely heavily on networks, reputation, terminal locations, and transport logistics. Transport costs and access to temporary storage and processing sites strongly influence whether circular mass management is feasible (Eriksson et al., 2025).

2.5 Legislative and Regulatory Frameworks for Excavated Soil Management in Selected European Countries

2.5.1 The Netherlands

In 2008, the Netherlands introduced the Soil Quality Decree, promoting sustainable land management by reusing soil and sediments near excavation sites (Gadella et al., 2012). This policy is based on two main principles: Standstill and Fit for use, outlined in Table 2-6 below, along with two additional principles (Gadella et al., 2012).

Table 2-6. Basic principles of mass handling according to the Dutch Soil Quality Decree (Bulletin of Acts, 2007).

Principles	Descriptions
Standstill	Applied soil should be of equal or better quality than the receiving soil.
Fit for use	On-site soil quality should correspond with its actual use.
Temporary storages	• By standard regulations, storage is permissible for up to three years. • "Stand still" must also be applied for temporary storage. It is required to report details concerning the excavation site, the quantity involved, the intended future use, the results of the soil quality survey, and other relevant survey reports to the competent authority.
Traceability	• Private person: no registration required. • For masses consisting of <50 m^3 of clean soil: no registration required. • Contaminated soil: Each volume of soil must be reported to a national registry. The national register informs the competent authority and the national environmental protection officer. • Clean soil: every useful application >50 m^3 must be reported to a national register. The national register informs the competent authority and the national environmental monitoring.

To apply these principles, it was essential to delineate land use functions and set new soil quality standards. Land uses for agriculture/nature, residential/urban, and industrial purposes were defined based on levels of protection for human health, ecosystems, and agricultural risk (Gadella et al., 2012). Based on the 2011 policy evaluation and feedback, all municipalities and water authorities implemented the policy to balance soil supply and demand (Gadella et al., 2012).

In 2022, a collaboration between various stakeholders, based on a task assigned by the Dutch Department of Waterways and Public Works, resulted in the first proof of concept for the Dutch Soil Passport. This tool assists in tracking important information such as the amount of soil excavated, the entity responsible for transportation, and the characteristics of the soil (Ledger Leopard, 2023). For more information, see Subsection 8.3.4.

In 2022, a Water and Soil-based planning policy was introduced to support healthy soil maintenance (Personal Communication Maring, 2024). This policy specifies methods to achieve this goal, focusing on preserving natural resources by reducing unnecessary excavation and destruction (Personal Communication Maring, 2024). The soil disturbance and reuse measures aim to minimize excavation and provide alternatives. The policy encourages reusing excavated soil to the highest possible quality and as much as possible in situ. If reuse within the project is not feasible, the soil is reused within the area, with a preference for high-quality use (Personal Communication Maring, 2024).

2.5.2 France

The reuse of excavated soil in France is determined by the level of contamination at the excavation site (French Environment Agency, 2018; NF X 31-620-2; French Standard, 2018). Should the site be classified as contaminated, it is subject to national regulations for contaminated areas. In such instances, the excavated soil may undergo on-site treatment to eliminate contaminants (French Environment Agency, 2018). Conversely, if there is no contamination, the excavated soil is classified as natural material. In cases like this, provided the geotechnical properties are satisfactory, the soil can be utilized in earthmoving programs, that is, operations related to the movement, excavation, or displacement of large amounts of soil, rock, or other materials from one location to another (Perth Earthmoving, n.d.), across different sites (Hale et al., 2021). Under environmental regulations, excavated soil transported off-site is classified as waste (Hale et al., 2021). However, these soils can be enhanced and reused if specific conditions are satisfied: (1) the soil quality at the receiving site must be maintained, (i.e. the Standstill principle in the Netherlands) ensuring that the chemical properties of the excavated soil align with the geochemical background of the recipient site; (2) the quality of water resources at the recipient site must remain unaffected and its ecosystems must be preserved, and (3) the chemical characteristics of the excavated soils must be compatible with the intended use at the recipient site (i.e. the Fit for use principle in the Netherlands) (Hale et al., 2021).

The excavated soil can be reused for road construction per French national requirements and in development projects approved by competent authorities, following French urban or environmental legislation (Blanc et al., 2012).

2.5.3 Belgium

Wallonia and Flanders, two regions in Belgium, have distinct regulatory approaches to land management and soil quality. Wallonia adopts a general framework, AGW Terres Excavées, focused on land use and soil quality, with strict criteria to ensure environmental safety, including a preventive inspection system. The soil passport guarantees the tracking of excavated material. Flanders emphasizes environmental protection with a broader framework (Decree on soil remediation and soil protection:VLAREBO) that covers various materials and land uses, ensuring imported soil does not harm receiving sites. The region follows a standstill principle and provides detailed requirements for physical contaminants. This means contamination is managed according to the intended reuse and land use of excavated materials: clean soil can be used freely, slightly contaminated soil is limited to certain projects (construction projects, like bridges or other building projects), and heavily contaminated soil must be treated before reuse. Traceability is not mandatory, though desirable. In both regions, regional licensing bodies oversee operations and issue permits.

2.5.4 Norway

The Norwegian Environment Agency regulates the reuse of clean soil and stones. Their guidelines address intermediate storage, final disposal, and reuse (Norweigan Ministry of Climate and Environment, 2019). To reuse clean excavated soil and stones, the following criteria must be met: (1) site development is independent of the availability of clean excavated soil and stones, (2) sufficient material is available for reuse, and (3) the materials are suitable for reuse (Hale et al., 2021). Currently, there are no specific guidelines governing the reuse of contaminated soil. However, it is possible to apply for a permit for such reuse. In this context, if the contaminant levels in the soil do not exceed specified threshold concentrations, a risk assessment must be conducted to identify any potential hazards to the surrounding environment (Hale et al., 2021). On the contrary, if the threshold concentrations are exceeded, the soil is classified as contaminated. In Norway, surplus excavated soil that is not used within the project is generally classified as waste material (Hale et al., 2021).

2.5.5 Finland

In Finland, the waste management law, Jätelaki 646/2011, defines the criteria for classifying materials as either waste or non-waste (The Ministry of the Environment, 2011). Materials classified as waste are those that the owner has disposed of, plans to dispose of, or is required to dispose of. On the other hand, if the material is produced during a production process and meets certain requirements, it is referred to as a by-product (The Ministry of the Environment, 2011). Additionally, if the following criteria are met, the material will no longer be considered waste (The Ministry of the Environment, 2011):

- It has been recycled.
- It has a common use.
- There is a market or demand for it.
- It meets technical and regulatory standards for its intended use.
- Its use poses no danger to the environment or human health.

In general, the legislation aims to support a CE. An illustrative example is the pilot project conducted between 2011 and 2013 in Espoo, where low-quality soil was recycled through mass stabilization, a method involving the addition of binders to the soil to harden and strengthen it (Forsman et al., 2013).

2.5.6 United Kingdom

England and Wales apply the same waste definition principles as Finland. Under the WFD, soil is considered waste if the owner discards it, intends to discard it, or is required to discard it. However, in Scotland, soil becomes waste once it leaves the site (Plimmer, 2023).

Furthermore, uncontaminated natural soils excavated during construction projects may be reused on the same site for construction purposes (Plimmer, 2023). Additional regulations and exemptions must be met if the soil is intended for use as filling material on another site. In such cases, the Environment Agency provides a U1 Exemption, which is free of charge but limited to 1,000 tonnes (Plimmer, 2023).

Additionally, the CL:AIRE Definition of Waste Code of Practice (DoW CoP), a voluntary scheme applied to England and Wales, assesses, on a site-specific basis, whether excavated materials should be classified as waste. It also determines, on a site-specific basis, when treated excavated waste can be regarded as no longer being waste for a particular use (Duckworth, 2011). CL:AIRE, a UK-based charity focused on sustainable land reuse, under which DoW CoP offers a clear process for reusing excavated materials on-site or moving them between sites (CL:AIRE, n.d.-b). The DoW CoP concerns the excavated materials listed in Table 2-7 below.

Table 2-7. Material types under DoW CoP, from (Duckworth, 2011).

Material Type	Description
Soil	Top-soil and sub-soil, parent material, and underlying geology
Soil and mineral based dredgings	Dredged material will not be deemed suitable for use until it has undergone sufficient dewatering and is classified as waste. Once it is confirmed that no additional treatment is necessary, the dredged material can be utilized in earthworks as non-waste.
Ground based infrastructure	Capable of reuse within earthworks projects, e.g. road base, concrete floors
Made ground	
Source-segregated aggregate material	Arising from demolition activities, such as crushed brick and concrete, to be reused on the site of production within earthworks projects or as sub-base or drainage materials
Stockpiled excavated materials	Include the above

Launched in 2008, DoW CoP has issued nearly 11,000 declarations, impacting the sustainable use, transfer, and reuse of approximately 250 million m^3 of soil and excavated materials that would otherwise be treated as waste (Froggatt, 2023). Furthermore, CL:AIRE manages projects like the Register of Materials (CL:AIRE, n.d.-a), described in Subsection 8.3.6, and the Earthbanks Project (CL:AIRE, 2024).

The classification of waste soil removed from the site will determine whether it is categorized as hazardous waste (soil and stones containing hazardous substances) or non-hazardous waste, according to the Technical Guidance WM3: Waste Classification-Guidance on the classification and assessment of waste (Plimmer, 2023).

2.5.7 Portugal

The General Regulation of Waste Management, as outlined by the WFD, governs the handling of excavated soils during construction projects (Portugese Environment Agency, 2006). However, non-contaminated soils that meet the standards set by Ontario, Canada (including the prescribed contaminants and the applicable site condition standards for those contaminants for the purposes of Part XV.1 of the *Environmental Protection Act*) (Ministry of the Environment, 2011), along with other natural materials, are exempt from this regulation if they are utilized for construction purposes under the following conditions (Portugese Environment Agency, 2019): (1) on-site, in their natural state, or (2) off-site, in projects that require either licensing or prior notification to the responsible authorities. This includes their application in environmental and landscape restoration activities related to mining and quarrying, as final cover for landfills, or at locations approved by the City Hall (Hale et al., 2021). Excavated soil, whether uncontaminated or contaminated, is categorized as waste if it is not reused on-site or off-site (Hale et al., 2021).

2.5.8 Slovenia

In Slovenia, the management of excavated soil is governed by several regulations, including the Regulation on the Management of Waste arising from Construction Work (Slovenian Environment Agency, 2008). Under this regulation, the owner is responsible for managing construction waste on-site. If the soil is uncontaminated, it can be reused either on-site or off-site if owned by the same owner (Slovenian Environment Agency, 2008). By another regulation, The Regulation on Burdening of the Soil by Waste, excavated soil is classified as waste and its physicochemical properties must meet permissible concentration limits for reuse scenarios (Slovenian Environment Agency, 2011). These scenarios include soil recultivation, backfilling of agricultural land, backfilling of building land, and backfilling following excavation (Slovenian Environment Agency, 2011). Reusing excavation materials is classified as waste recovery and needs an Environmental Permit from the Slovenian Environmental Agency, granted upon providing adequate documentation and meeting concentration levels (Hale et al., 2021).

2.6 Other countries

For insights into how excavated soil/mass management is handled in other parts of the world, such as Japan and Australia, see (Jansson & Olsson, 2024) and (Andersson & Borre, 2024).

2.7 Identification of good practices in mass management in the selected countries

The reviewed regulatory framework in countries such as the Netherlands, Belgium, the UK, and France indicates that current governance frameworks facilitate the management of excavated soil, promoting more circular and sustainable approaches. Both the Netherlands and Belgium adhere to the Standstill principle and have introduced the Soil Passport, which aids in tracking excavated materials. This aligns with the European Commission's planned actions, as described earlier in the text. In the UK, the CLA:IRE Definition of Waste Code of Practice, together with the Register of Materials, has also influenced the reuse of excavated materials. These initiatives in both the Netherlands and the UK have significantly contributed to the reuse of large volumes of soil, soil products, and other excavated materials. In 2020, the Netherlands processed 2.7 million tons of contaminated soil through methods like cleaning, immobilization, or landfilling. Additionally, 46.2 million tons of soil were directly applied in various projects, such as noise barriers and road foundations. Furthermore, 1.8 million tons of dredged material were processed, and 6.3 million tons were directly used in (water) soil applications. As mentioned, the scheme implemented in the UK led to the reuse of around 250 million m^3 of soil and excavated materials between 2008 and 2022.

In Sweden, the primary legislation is the Swedish Environmental Code, which follows the WFD definition of waste. However, this alignment does not inherently provide specific support for the management or potential reuse of excavated materials. At the same time, awareness among stakeholders involved in excavated soil management has increased, and several initiatives (discussed later in the text) have been introduced to promote more sustainable and circular approaches to mass management. Nevertheless, the regulatory framework could be further adapted to better encourage the reuse of excavated materials, as demonstrated in the Netherlands.

3 The concept of Sustainable development

Almost forty years ago, the definition of sustainable development, published in *Our Common Future,* known as the Brundtland Report, stated that “to reach sustainable development, the needs of the present generation must be met without compromising the ability of future generations to meet their own needs” (Hedenus et al., 2018). The modern concept of sustainability, however, can be traced back to forestry, specifically to the silvicultural principle that the volume of wood harvested should not surpass the amount that regenerates. This principle was first documented in the early 18th century in *Sylvicultura oeconomica* (Von Carlowitz, 1732). Over time, the concept was adapted to the field of ecology, emphasizing the importance of respecting nature's capacity to regenerate itself (Duden, 2015). This eventually led to the modern definition of sustainability as the ability to "be maintained at a certain rate or level" (Dictionary, 2010). The term "sustainability" comes from the French word *soutenir*, meaning "to hold up or support" (Brown et al., 1987). According to (Johnston et al., 2007), there are over 300 definitions of sustainability. However, the definition provided by the Brundtland Report continues to be one of the most widely accepted today (Geissdoerfer et al., 2017).

Regarding key works that have shaped the concept of sustainable development, the first significant wake-up call for environmental issues was the publication of *Silent Spring* in 1962. It garnered widespread attention as a concrete example of the negative impact of industrialization and the limitations of the environment's ability to absorb pollutants (Hedenus et al., 2018).

In 1972, the first international environmental conference was held in Stockholm and led to the establishment of the United Nations (UN) Environment Programme. However, poorer nations were skeptical, seeing the environmental agenda as a threat to their growth. This resistance highlighted the need to balance the development rights of poorer nations with the growing awareness of environmental limitations (Hedenus et al., 2018).

In 1983, the UN established the World Commission on Environment and Development to address increasing criticism of the environmental movement. Chaired by former Norwegian Prime Minister Gro Harlem Brundtland, the commission comprised officials and decision-makers from 21 countries to tackle environmental and development challenges. To ensure a broad range of viewpoints, public surveys were conducted worldwide. In 1987, the commission presented its findings in *Our Common Future*, also known as the Brundtland Report (Hedenus et al., 2018).

The 1992 UN Conference on Environment and Development in Rio de Janeiro is regarded as a milestone in the environmental movement and global environmental engagement. Although the agreements were non-legally binding, the conference's principles had a lasting impact on sustainable development worldwide. Key outcomes included Agenda 21, which outlined 120 action initiatives, the Rio Declaration emphasizing the precautionary principle, and the establishment of the UN Convention on Biological Diversity (UNCBD) and the Framework Convention on Climate Change (UNFCCC). The latter led to subsequent negotiations that produced a protocol to reduce greenhouse gas emissions (GHG) in developed countries, the Kyoto Protocol (Hedenus et al., 2018).

In 2000, the UN adopted the Millennium Declaration, outlining eight goals to be achieved by 2015. Supported by 189 member states and 23 international organizations, the Millennium Development Goals (MDGs) primarily focused on development, with just one goal directly addressing environmental issues (Hedenus et al., 2018).

The 2002 Rio+10 conference in Johannesburg, South Africa, garnered less attention and is seen as less significant than the 1992 conference. Nevertheless, it initiated a clearer conversation on the importance of integrating the ecological, economic, and social dimensions of sustainable development, as seen later in the text (Hedenus et al., 2018).

The 15th Conference of the Parties (COP 15) for the UNFCCC was held in Copenhagen in December 2009, aiming to establish a global climate agreement. The Copenhagen Accord was adopted, emphasizing the need to limit global temperature rise to below 2°C above pre-industrial levels. The accord included emission reduction commitments from both developed and developing countries, though these commitments were non-legally binding (C. C. United Nations, n.d.).

In 2012, the Rio+20 conference was held in Rio de Janeiro, where negotiations began on new goals to replace the MDGs after 2015 (Hedenus et al., 2018). The key works that have shaped the concept of sustainable development can be summarized in Figure 3-1 below.

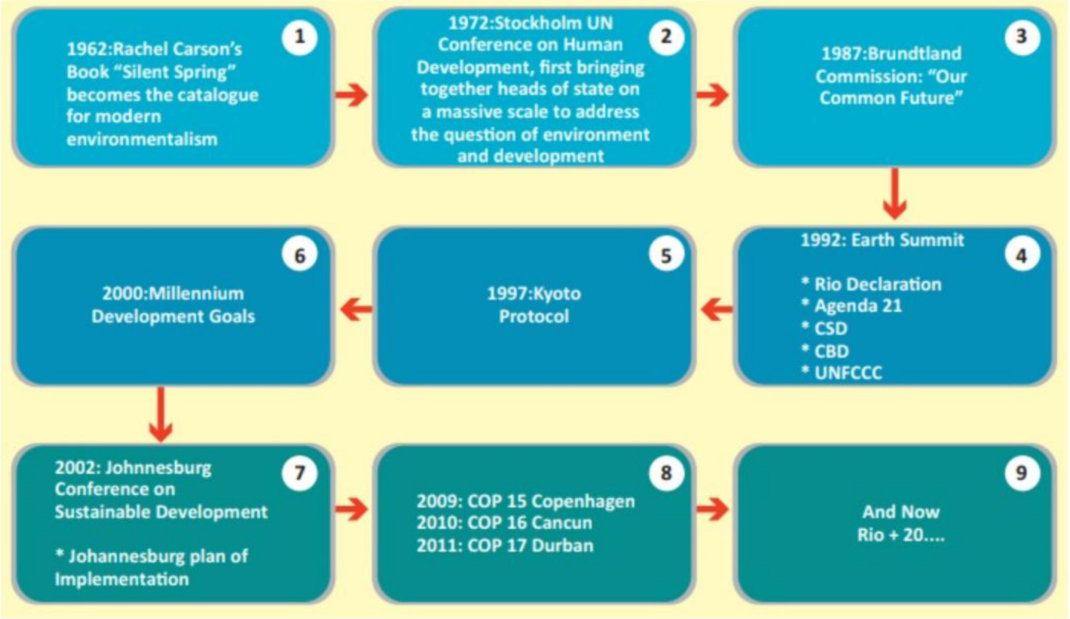


Figure 3-1. Development of the concept of sustainable development, from (BrainKart, n.d.).

3.1 Sustainable Development Goals (SDGs)

In 2015, the MDGs were expanded and transformed into the Sustainable Development Goals (SDGs) (Ortiz-de-Montellano et al., 2023), which encompass 17 goals and 169 targets, see Figure 3-2, addressing a wide array of issues and integrating environmental concerns with development (Hedenus et al., 2018; United Nations Department of Economic and Social Affairs, n.d.). Unlike the MDGs, the SDGs include specific targets for areas such as cities, sustainable consumption, climate change, marine resources, and land ecosystems. While the MDGs primarily focused on the world's poorest countries, the SDGs aim to engage all nations in acting. Key principles of the SDGs include goal integration, a holistic approach, fostering synergies between goals, ensuring progress in all areas, and recognizing potential trade-offs (Hedenus et al., 2018).

Figure 3-2. Sustainable Development Goals, from (United Nations, n.d.).

As highlighted in the introduction, given the growing effects of urbanization and its harmful impact on the environment, the building and construction sector plays a significant role in CO_2 emissions and energy consumption. Infrastructure projects are responsible for extracting 50% of the world's finite natural resources and generating 25% of annual waste in Europe, with a large portion of this waste coming from excavated materials that are sent to landfills. These figures emphasize the critical need for further actions and efforts to promote sustainable development within society. In this context, SDG 3, *Good Health and Well-being*, focuses on ensuring healthy lives and promoting well-being for individuals of all ages. SDG 9, *Industry, Innovation, and Infrastructure*, focuses on building resilient infrastructure, promoting inclusive and sustainable industrialization, and encouraging innovation. SDG 11, *Sustainable Cities and Communities*, strives to make cities and human settlements inclusive, safe, resilient, and sustainable. SDG 12, *Responsible Consumption and Production*, advocates for sustainable patterns of consumption and production, while SDG 13, *Climate Action*, emphasizes the need for urgent action to tackle climate change and its consequences. Additionally, SDG 15, *Life on Land*, aims to address and reverse land degradation, among other objectives (United Nations Department of Economic and Social Affairs, n.d.). Collectively, these SDGs tackle the environmental and social challenges outlined above.

3.2 Three dimensions of sustainable development

According to (Hedenus et al., 2018), when addressing the three dimensions of sustainable development, it is helpful to distinguish between three components: ends, means, and preconditions. In this framework, the ultimate goal is to fulfill human needs. To accomplish this, various means can be utilized, such as ensuring the rights of all individuals or promoting economic growth that generates resources. However, all these means depend on foundational preconditions. As a result, the three dimensions of sustainable development can be viewed as essential preconditions for implementing various means that foster sustainable development (Hedenus et al., 2018). The Brundtland Report outlined the ecological, economic, and social dimensions of sustainable development, which have since been interpreted in multiple ways (Hedenus et al., 2018). The three dimensions can be illustrated in different ways, as demonstrated in Figure 3-3 below.

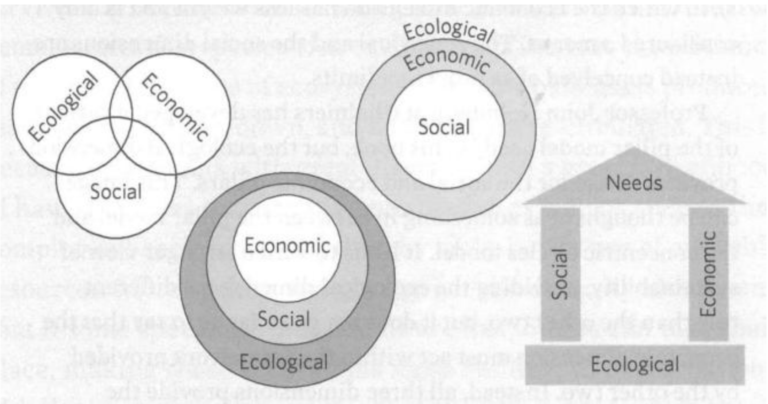


Figure 3-3. Three dimensions of sustainable development, from (Hedenus et al., 2018).

3.2.1 The ecological dimension of sustainable development

The ecological dimension is concerned with preserving natural systems that deliver vital benefits to humans. It encompasses two key aspects: environmental production capacity and environmental assimilative capacity. Environmental production capacity involves nature's ability to provide resources such as cropland, clean water, fisheries, and forests for food, fuel, and other needs. Furthermore, the environment contributes ecosystem services, recreational benefits, and, for certain groups, spiritual or religious values. Environmental assimilative capacity refers to the ability of natural systems to manage various pollutants and environmental impacts. For example, the oceans can absorb large quantities of carbon dioxide, and environmental processes break down chemicals into less harmful forms (Hedenus et al., 2018).

3.2.2 The economic dimension of sustainable development

The economic dimension focuses on managing the resources needed to fulfill human needs. It can be divided into two parts: finite natural resources and man-made capital. Finite natural resources include fossil fuels, metals, and phosphorus, substances extracted from the Earth's crust that are not part of the ecological system and are non-renewable. Man-made capital refers to assets created by humans to produce goods and services, such as buildings, factories, knowledge, and human capital. When it comes to economic growth, it is often viewed as a potential means of meeting human needs, though it should not be regarded as essential for sustainable development, even though it holds significance in certain areas. Additionally, it is debated as a possible long-term risk to the ecological aspect of sustainability, as uncontrolled growth could overburden environmental resources (Hedenus et al., 2018).

3.2.3 The social dimension of sustainable development

The social dimension of sustainable development is less explored in the literature (Hedenus et al., 2018). While topics like health, human rights, and fair resource distribution are commonly seen as core aspects, (Hedenus et al., 2018) argue that they should be viewed as means or ends rather than part of the social dimension itself. He suggests that the social dimension should be a precondition for addressing human needs. (Holmberg & Larsson, 2017) propose dividing it into vertical relations (formal institutions with hierarchical structures) and horizontal relations (networks formed by individuals and organizations) (Hedenus et al., 2018).

3.3 Doughnut concept and Doughnut economics

Framework for sustainable development (Raworth, 2012), introduced in 2012 through an Oxfam report by Kate Raworth, the Doughnut concept quickly gained global attention (Doughnut Economics Action Lab, n.d.). It outlines a vision for what it means for humanity to thrive in the 21st century, while Doughnut Economics (DE) explores the mindset and approaches needed to achieve this vision (Doughnut Economics Action Lab, n.d.). The Doughnut comprises two concentric rings, as shown in Figure 3-4: a social foundation, that is human rights, ensuring everyone has access to life’s essentials, and an ecological ceiling that embodies planetary boundaries, preventing humanity from exceeding the planet's limits that protect Earth's life-supporting systems. Between these two boundaries lies a doughnut-shaped space where humanity can thrive, in an environment that is both socially just and ecologically safe (Doughnut Economics Action Lab, n.d.; Raworth, 2012).

The planetary boundaries concept, introduced by the Stockholm Resilience Centre in 2009, identifies nine critical Earth-system processes vital for sustainable development. These processes have "tipping points" where exceeding certain thresholds could trigger irreversible environmental changes, shifting Earth away from its stable Holocene state. Such changes would disproportionately affect vulnerable populations, particularly those living in poverty who depend on natural resources for their livelihoods. To reduce risks, it is essential to establish safe boundaries for each process, creating what is known as a "safe operating space for humanity" (Raworth, 2012).

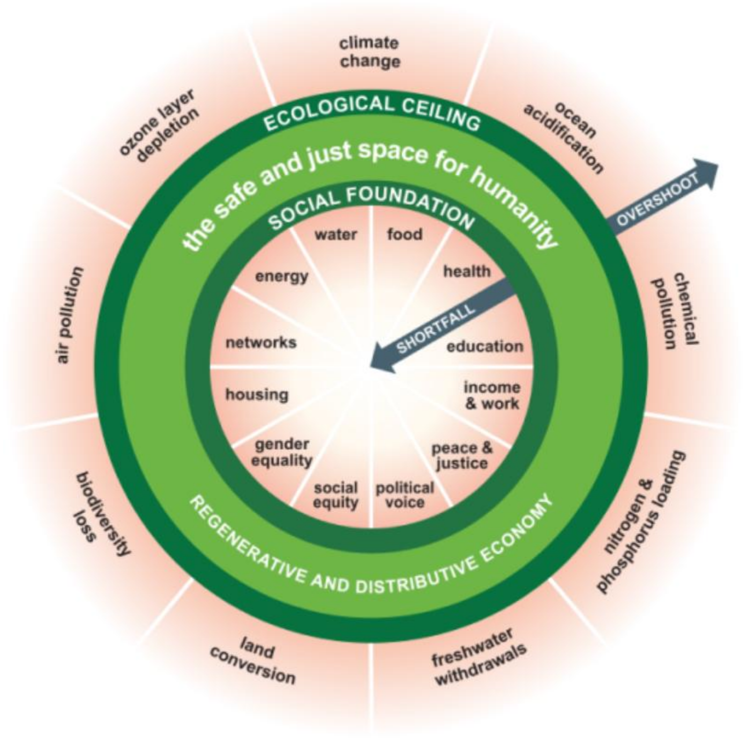


Figure 3-4. The Doughnut of social and planetary boundaries, from (Doughnut Economics Action Lab, n.d.).

Additionally, rather than a set of policies or institutions, DE provides a way of thinking that fosters the regenerative and distributive dynamics needed in this century. It outlines seven key ways of thinking like a 21st-century economist to transform economies at every level, from local to global scales (Doughnut Economics Action Lab, n.d.). At its core, DE shifts the goal from endless GDP growth to thriving within Doughnut's safe and just space. It encourages seeing the bigger picture and understanding that the economy is deeply intertwined with society and the natural world. It also recognizes that economies, societies, and ecosystems are complex, interconnected systems best understood through systems thinking. The framework advocates for transforming today's degenerative economies into regenerative ones and moving from divisive to more distributive economies. Finally, DE understands that while growth is a natural and healthy phase of development, nothing grows forever (Doughnut Economics Action Lab, n.d.).

A prime example of a city embracing the Doughnut framework and DE can be found in Amsterdam. In 2020, Amsterdam became the first city in the world to adopt a DE model as part of its Circular Strategy 2020-2025 (DEAL, 2020; O'Connor, 2024). The city aims to be fully circular and climate-neutral by 2050. Amsterdam's circular model focuses on three main value chains: food and organic waste, consumer goods, and the built environment. The city plans to cut primary raw material consumption by 50% and introduce a 'material passport' for buildings to ensure that construction materials are renewable and valuable, among other initiatives (DEAL, 2020; O'Connor, 2024).

4 The concept of Circular Economy

The CE concept has diverse origins, with different researchers presenting varying views on its sources of inspiration. Nevertheless, research from (Ellen MacArthur Foundation, 2018; Prendeville et al., 2017; Winans et al., 2017) highlights two common conclusions: 1) circularity is not a new concept; it has existed in different forms over time, and 2) the book Cradle to Cradle (Braungart & McDonough, 2002) played a significant role in shaping the development of CE.

Published in 2002, Cradle to Cradle promotes a vision of a waste-free world, going beyond traditional "eco-efficient" (described later in the text) approaches that focus on reducing environmental harm. It suggests that waste is a design flaw and encourages the recovery and reuse of materials. In 2010, the Cradle to Cradle™ certification process (Braungart & McDonough, 2009; C2C, 2018) was introduced to evaluate product sustainability. The philosophy also advocates renewable energy and values natural diversity instead of industrial uniformity. Its successful application depends on strong stakeholder collaboration and social responsibility. For other sources of origin of CE, please refer to (Chowdhury, 2020).

4.1 Definitions of CE

In 2002, China adopted CE as a national development strategy to foster sustainable urban growth and achieve a balance between rural and urban areas. Specifically, waste reduction and resource reallocation were seen as effective strategies to encourage rural populations to stay in rural areas (Kalmykova et al., 2018). The goal of China's CE strategy, as outlined in the study by (Yuan et al., 2006) is to create closed loops for energy and material cycles. This aligns with the Chinese government's definition of CE, which emphasizes the "realization of a closed-loop material flow throughout the entire economic system" (Geng et al., 2009).

In 2014, the CE concept was introduced into EU policy when the EC initiated discussions on a legislative package based on the CE model (Ekins et al., 2020). The first CE Action Plan was published and implemented in 2015 (European Commission, 2015). The second CE Action Plan was published in 2020, further reinforcing the CE as the key concept that shapes the EU's economic vision and its approach to achieving sustainable development (European Commission, 2020). According to the European Parliament, the CE is a model of production and consumption that emphasizes prolonging product life cycles through methods such as sharing, leasing, reusing, repairing, refurbishing, and recycling. Its goal is to reduce waste by retaining materials within the economy through recycling, enabling their continuous reuse to generate added value. This approach stands in contrast to the traditional linear economic model, see Figure 4-1 and Figure 4-2 which follows a take-make-consume-dispose cycle and relies on abundant, inexpensive, and easily available materials and energy (European Parliament, 2023).

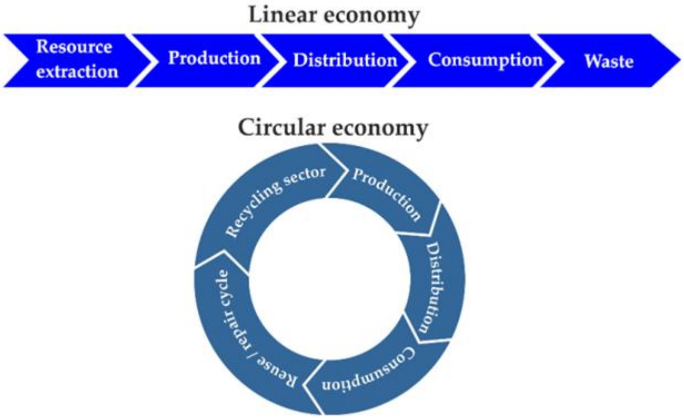


Figure 4-1. Linear vs. Circular economy, after (Fura et al., 2020).

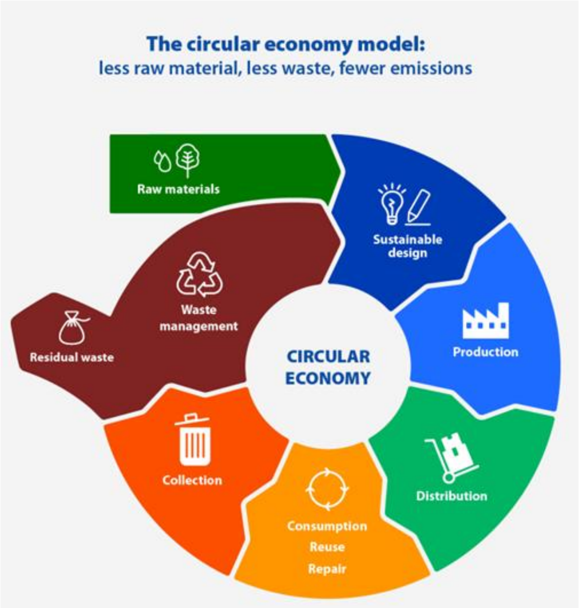


Figure 4-2. The circular economy model, after the European Parliament Research Service (European Parliament, 2023).

The concept of CE has diverse definitions, making it challenging to conceptualize. (Kirchherr et al., 2017) analyzed 114 definitions and proposed a unified definition that captures CE's core principles. CE is an economic system that replaces the 'end-of-life' concept with strategies like reducing, reusing, recycling, and recovering materials. It operates at micro, meso, and macro levels to achieve sustainable development by promoting environmental quality, economic prosperity, and social equity (Kirchherr et al., 2017). This system is supported by innovative business models and responsible consumer behavior, providing a foundation for future CE research (Kirchherr et al., 2017).

Furthermore, (Kalmykova et al., 2018) reviewed CE theories and practices and found that a shared principle across various CE definitions and approaches is the focus on maximizing the value of the resources in use, which can also be defined as “stock optimization”. Another common principle that has been identified in the CE approaches is Eco-efficiency, which is defined as an approach focused on minimization and dematerialization, aiming to reduce the volume, speed, and toxicity of material flows (Ellen MacArthur Foundation, 2013). However, in the report "*Towards the circular economy Vol. 1: An economic and business rationale for an accelerated transition",* authors suggest that the focus should shift from eco-efficiency to eco-effectiveness, where the goal is not to minimize the cradle-to-grave flow of materials but rather to create cyclical, cradle-to-cradle "metabolisms" that allow materials to retain their value as resources, see Section 7.2 (Ellen MacArthur Foundation, 2013). In addition to these two approaches, waste prevention and the Rs (discussed later in the text) are also represented (Kalmykova et al., 2018).

The CE definition presented in the same report (Ellen MacArthur Foundation, 2013), which appears to be the most widely adopted (Geissdoerfer et al., 2017), describes the CE as an industrial economy designed to be restorative by intention. It aims to depend on renewable energy, minimize, monitor, and eliminate the use of toxic chemicals, and eliminate waste through thoughtful design (Ellen MacArthur Foundation, 2013).

In a more recent study, (Kirchherr et al., 2023) reviewed 221 CE definitions and found that, while the concept has become more established, it also continued to evolve and diversify. Their analysis indicates that many emerging definitions are more aligned with academic discourse than with practical implementation. At the same time, there is a growing emphasis on the need for fundamental systemic transformation, particularly within supply chains, to enable the transition to a CE. Although sustainable development remains a primary objective, uncertainties persist regarding the extent to which CE practices can simultaneously support environmental sustainability and economic growth. Finally, the authors highlight that achieving a successful transition depends on the active collaboration of a wide range of stakeholders, including producers, consumers, policymakers, and researchers (Kirchherr et al., 2023).

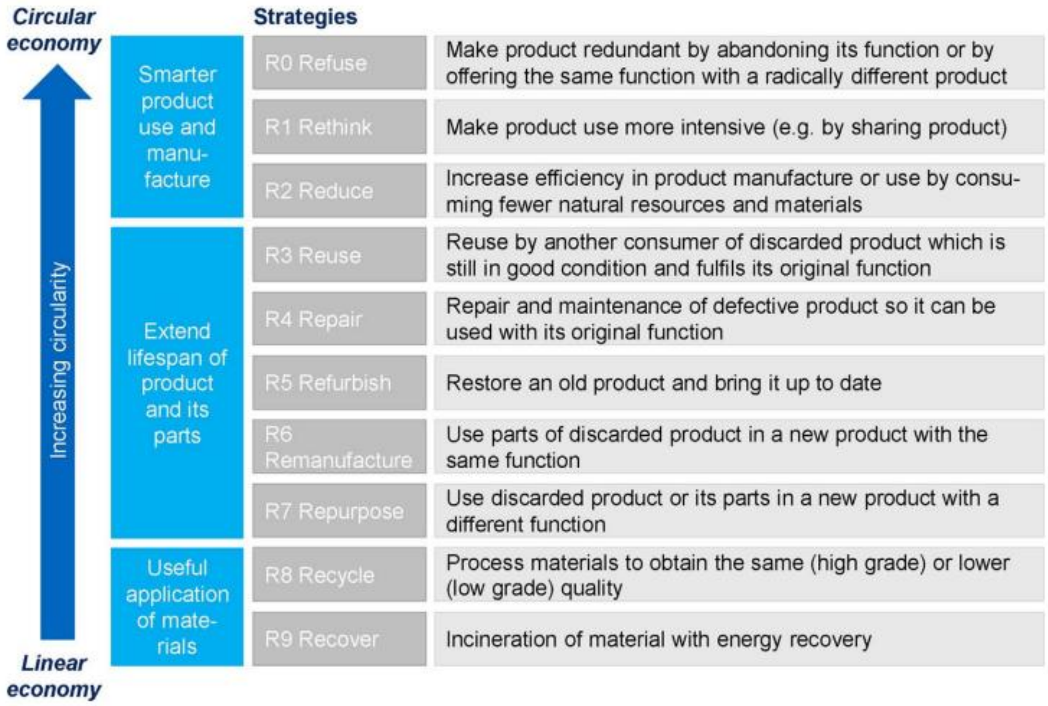
4.2 The R Framework

The 3 Rs - reduce, reuse, and recycle- are derived from the waste hierarchy, though their application differs across countries (Sakai et al., 2011). For example, China officially incorporated the 3R framework into its CE strategy around 2002 (Yang et al., 2014), while in the EU, the 4R framework was introduced as a part of WFD in 2008 (European Parliament and the Council, 2008). The 4R framework is presented in Table 4-1 below.

Table 4-1. 4R Framework, from (Chowdhury, 2020), adapted from (Hu et al., 2011).

Level 1: Reduce	Reduce the consumption of resources and the production of waste in the processes of production, circulation, and consumption.
Level 2: Reuse	Use waste as products, either in the same function or in another.
Level 3: Recycle	Use the waste as raw materials after simple treatment, such as collection, separation, and suitable modification, during which core physical and chemical properties should remain.
Level 4: Recover	Use the waste as products or raw materials after technical treatment, during which the core physical or chemical properties change depending on the feeding condition.

As can be seen in Figure 4-3 below, the R framework continues to evolve, with up to 9 Rs now being developed (Kirchherr et al., 2017).



	Strategies	
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

Figure 4-3. The 9R framework; from (Kirchherr et al., 2017).

4.3 The Butterfly Diagram

The butterfly diagram, shown in Figure 4-4, illustrates the CE system, highlighting the ongoing flow of materials within this framework. It is made up of two primary cycles: the technical cycle and the biological cycle. The technical cycle involves processes that ensure products and materials retain their maximum value over time (Ellen MacArthur Foundation, 2021). Materials suitable for this cycle are those that do not get consumed during use, such as metals, plastics, and wood. In this cycle, products and materials remain in circulation through practices like reuse, repair, remanufacturing, and recycling. In this context, reuse refers to the repeated use of a product or component for its intended purpose without significant modification (Ellen MacArthur Foundation, 2021). Repair is the process of restoring a faulty or damaged product or component to a functional state, allowing it to fulfill its intended purpose. Remanufacturing is the process of refurbishing products and components to bring them back to a like-new condition, achieving the same or enhanced performance as when they were originally manufactured (Ellen MacArthur Foundation, 2021). The biological cycle, on the other hand, includes processes such as composting and anaerobic digestion, which work together to restore natural capital. This cycle is only applicable to materials that can be safely returned to the biosphere, aiding in the regeneration of nature (Ellen MacArthur Foundation, 2021).

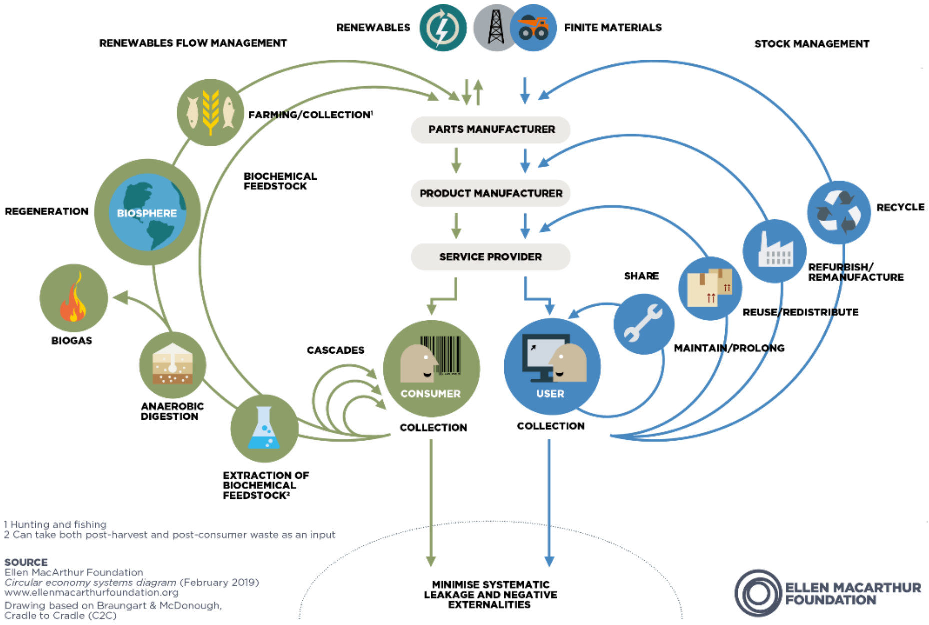
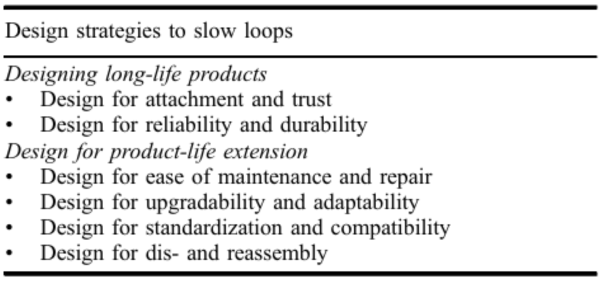


Figure 4-4. The butterfly diagram: visualizing the circular economy, from (Ellen MacArthur Foundation, 2021).

4.4 Slowing, closing, narrowing, and regenerating resource loops

(Bocken et al., 2016) proposed a framework to help designers and business strategists move from a linear economy toward a circular one, building on earlier ideas by (Stahel, 2010). In this framework, they describe three key approaches: slowing, closing, and narrowing resource loops.

Slowing resource loops focuses on extending the lifespan of products. This can be achieved by designing durable goods and enabling product-life extension through activities such as repair or remanufacturing. By keeping products in use for longer periods or increasing how intensively they are used, the overall flow of resources is reduced (Bocken et al., 2016). Figure 4-5 illustrate strategies for slowing resource loops with detailed explanations of each strategy provided in (Bocken et al., 2016).



Design strategies to slow loops
Designing long-life products
• Design for attachment and trust
• Design for reliability and durability
Design for product-life extension
• Design for ease of maintenance and repair
• Design for upgradability and adaptability
• Design for standardization and compatibility
• Design for dis- and reassembly

Figure 4-5. Overview of design strategies to slow resource loops. From (Bocken et al., 2016).

Closing resource loops refers to recycling processes that reconnect end-of-life products back into production systems. This creates a circular flow of materials, where resources are continuously reused rather than discarded (Bocken et al., 2016). Figure 4-6 presents strategies to close resource loops, while a comprehensive description of each approach is available in (Bocken et al., 2016).

Design strategies to close loops
• Design for a technological cycle
• Design for a biological cycle
• Design for dis- and reassembly

Figure 4-6. Overview of design strategies to close resource loops. From (Bocken et al., 2016).

Narrowing resource loops emphasizes efficiency, aiming to reduce the amount of resources required to produce a product. In other words, it involves minimizing material and energy use throughout production and design processes (Bocken et al., 2016).

In short, slowing loops refers to prolonging the use of products, closing loops involves bringing materials back into use through recycling, and narrowing loops focuses on minimizing the amount of resources required (Bocken et al., 2016).

Furthermore, (Konietzko et al., 2020) expanded on the previously discussed approaches of slowing, closing, and narrowing resource loops by introducing a fourth concept: *regenerate*. This approach emphasizes the use of non-toxic materials, renewable energy, and the restoration of natural ecosystems, see Figure 4-7.

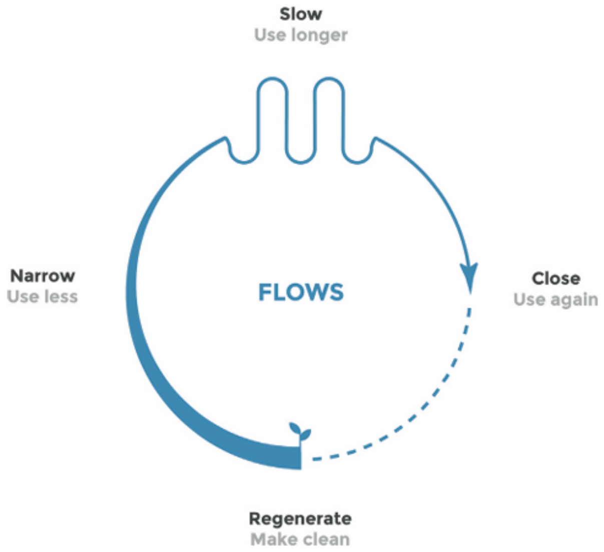


Figure 4-7. A CE: narrow, slow, close, and regenerate material and energy flows, from (Konietzko et al., 2020).

Drawing on product design and business model strategies that support the transition to a CE, (Bocken et al., 2016) developed a conceptual framework to guide this shift, see Figure 4-8. They presented this framework as an initial step, offering both academics and practitioners an overview as well as practical guidance for adopting CE strategies (Bocken et al., 2016). A more detailed explanation of the framework is provided in (Bocken et al., 2016).

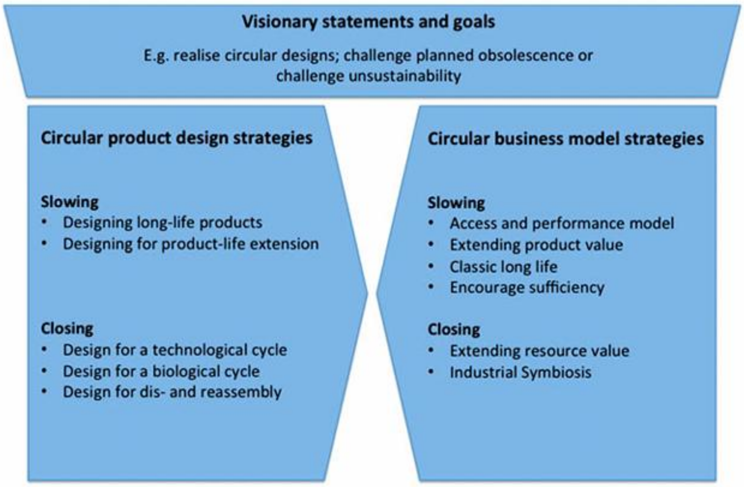


Figure 4-8. Circular economy product and business model strategy framework, from (Bocken et al., 2016).

4.5 Circular economy within the management of excavated soil

In 2020, ESR accounted for 20% of the total waste generated in Europe, which represents approximately 52% (444 Mt) of the CDW waste (848 Mt) in the region (Cristóbal et al., 2024). Despite this substantial volume, excavated soil was excluded from both the 70% recovery target for CDW set by the WFD for 2020 and the EU protocol for CDW (Cristóbal et al., 2024; European Commission: Joint Research Centre: Cristóbal García et al., 2023).

The report *"Techno-economic and environmental assessment of construction and demolition waste management in the European Union"* offers an overview of the current status and management of CDW in the EU, aiming to support future policymaking on CDW objectives related to preparing for reuse, recycling, and material-specific fractions in alignment with the WFD. According to the data presented in the report, the generation of CDW waste in Sweden, including soil, track ballast, dredging spoils, and asphalt, amounted to 13 megatons in 2020, with soil waste accounting for 8.9 megatons, i.e., 69% (European Commission: Joint Research Centre: Cristóbal García et al., 2023).

Furthermore, the report outlines the management options for various CDW material fractions as reported in the literature. Details for the excavated soil can be found in Table 4-2 below. It should be noted that only non-contaminated and non-hazardous waste is considered. For other CDW fractions, please refer to (European Commission: Joint Research Centre: Cristóbal García et al., 2023). It is important to note that from a CE perspective, the primary characteristics of excavated soil and dredging spoils are their composition, that is, particle size distribution - specifically the percentages of clay, silt, sand, and coarse materials - as well as the soil organic carbon content (g C kg^{-1} of soil) (Cristóbal et al., 2024).

Table 4-2. Management options reported in the literature for the excavated soil as CDW fractions, from (European Commission: Joint Research Centre, 2023).

Waste fraction	Management option	Main output	Potential material substituted
Excavated soil	Preparing for reuse	Soil	Sand/Gravel
	Recycling	Individual components (sand, clay)	Sand/Gravel Clay
	Recycling - stabilisation	Stabilized soil	Concrete or Sand/Gravel
	Recovery - backfilling	Soil	Sand/Gravel
	Landfilling	-	-

As can be seen in the table above, the three main management strategies for excavated soil are preparing for reuse, recycling into individual components and via stabilization, and recovery. A description of each strategy is provided below.

4.5.1 Preparing for Reuse

According to legislation, soil can be prepared for reuse and applied on-site or at other locations or projects, considering the material's suitability based on various practical and site-specific factors. When preparing excavated soil for reuse, it is important to evaluate geotechnical properties, including, e.g., cohesion, friction angle, grain size distribution, swelling potential, strength loss upon wetting, organic matter content, hydraulic conductivity, dry density, and shear strength (European Commission: Joint Research Centre: Cristóbal García et al., 2023; Kataguiri et al., 2019). These properties must align with the requirements of the receiving project, which could include applications like roadbeds, paving layers, or vegetation cover restoration, in addition to ensuring compliance with environmental safety standards (Kataguiri et al., 2019). The management of this process typically involves transporting the soil within the project site using machinery and compacting it (European Commission: Joint Research Centre: Cristóbal García et al., 2023).

Furthermore, (Haas et al., 2020) stated that the potential for reusing excavated rock and soil is determined by its geotechnical, petrophysical, mineralogical, and geochemical properties, along with the material management boundary conditions, as illustrated in Figure 4-9 below.

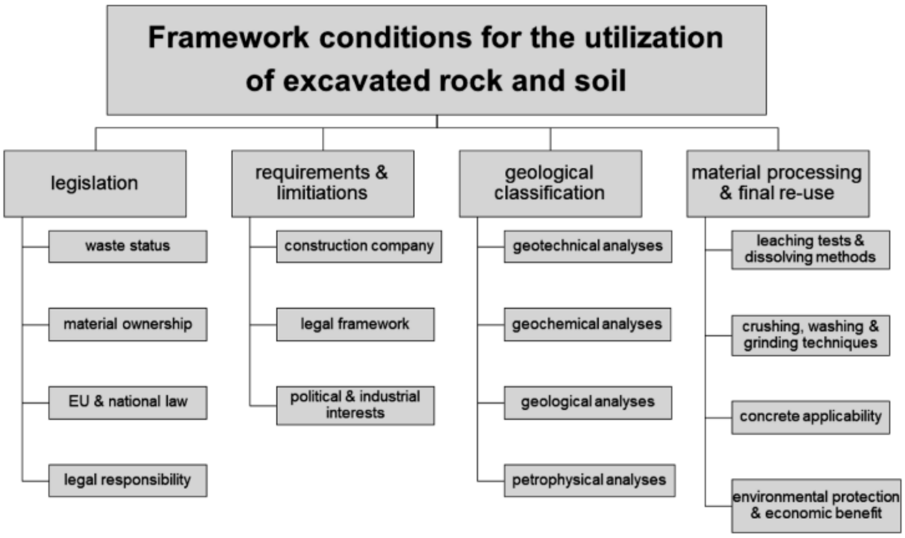


Figure 4-9. Reuse organigram for excavated rock and soil, specifying geology, processing techniques, and laws, from (Haas et al., 2020)

4.5.2 Recycling

Excavated soil can be recycled through stabilization or by separating it into individual components. Because of its poor strength, which makes it unsuitable for direct application in dams or roadbeds, some excavated soil requires stabilization (Huang et al., 2022) to improve its geotechnical properties, increase strength, and reduce permeability and compressibility (Magnusson et al., 2015). Common stabilization methods involve using cement, lime, fly ash, and fibers (Firoozi et al., 2017), along with other binders such as rice husk ash, bituminous materials, and synthetic substances (Afrin, 2017). The selection of binder depends on the soil type and the required properties, with lime being ideal for fine-grained soils and cement being suitable for most soil types with low organic content (Patel, 2019). Soil stabilization can take place either on-site or off-site. On-site methods eliminate the need for excavation, while off-site methods involve excavating, transporting, and mixing the soil with binders (European Commission: Joint Research Centre: Cristóbal García et al., 2023).

According to (Xu et al., 2022) sand and clay are the main components of excavated soil from underground infrastructure excavation, with sand making up 60% of the material. The remaining 40% is typically referred to as filter cake, as seen in Figure 4-10. The recycling process typically involves sorting, screening, crushing, sieving, iron removal, washing, chemical purification, and separating components such as clay and silt (Haas et al., 2020; Huang et al., 2022; Zhang, Zhang, et al., 2020). These components are treated with flocculants and sent to filter presses. The resulting filter cake, characterized by weak physical and mechanical properties, is often disposed of in landfills, causing significant harm to groundwater and soil resources (Duan & Li, 2016; Xu et al., 2022). However, research in Shenzhen, China, has focused on solidifying filter cake with cement and curing agents to produce recycled crushed aggregates (RCAs) (Xu et al., 2022). Admixtures are added to the filter cake and thoroughly mixed to improve bonding strength through cement hydration. The filter cake is then dehydrated into a block shape and crushed into irregular coarse and fine aggregates, similar to traditional stone aggregates. These angular RCAs are then recycled to create cement-treated base material (Xu et al., 2022), see Figure 4-10 below.

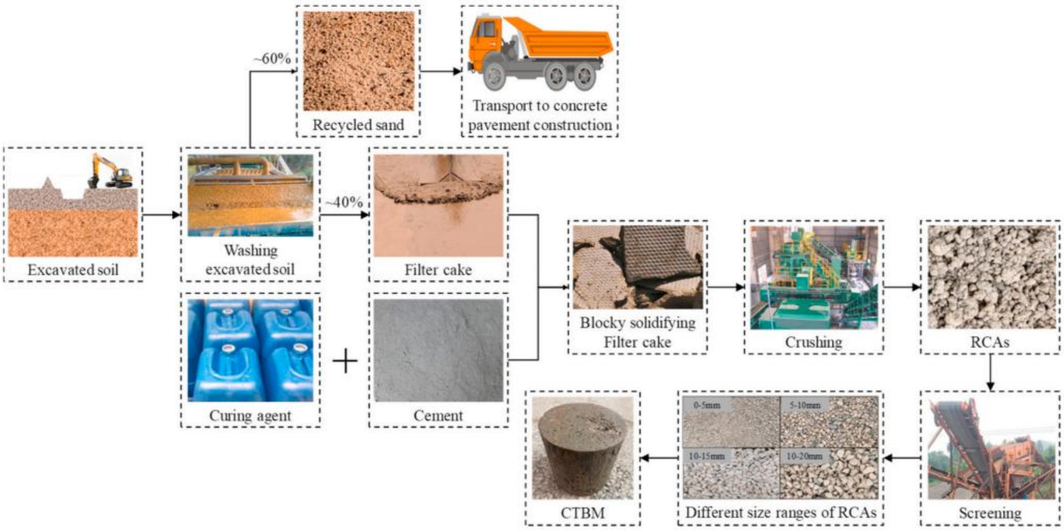


Figure 4-10. The main process of recycling filter cake to produce RCAs, from (Xu et al., 2022)

In addition to producing cement-treated base materials (Xu et al., 2022), certain recycling processes generate products like recycled bricks (Zhang, Zhang, et al., 2020) or concrete blocks (Luo et al., 2022). The process for recycling ESR and producing recycled bricks is depicted in Figure 4-11 and Figure 4-12 (Zhang, Zhang, et al., 2020).

Recycling method	Recycled product	Material to be replaced
Screening	Recycled sand (from ESR)	Natural sand (from river sediment)
Pressing	Recycled baking-free brick	Traditional clay solid brick
Baking	Recycled baked brick	Traditional clay solid brick
		Solid concrete brick

Figure 4-11. The recycle and replace scenario for ESR, from (Zhang, Zhang, et al., 2020).

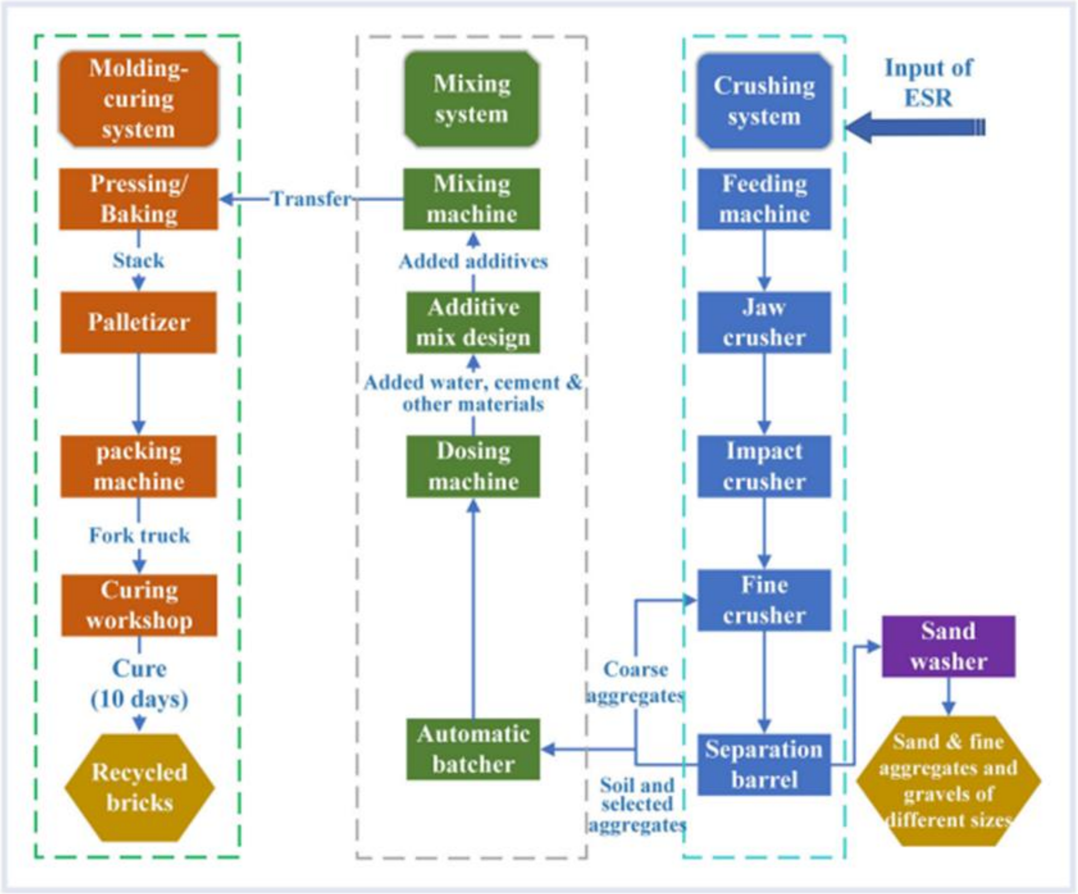


Figure 4-12. Schematic flowchart of recycling ESR, from (Zhang, Zhang, et al., 2020).

However, fully separating excavated soil into its individual material fractions (recycling) is rarely practiced due to economic constraints (European Commission: Joint Research Centre: Cristóbal García et al., 2023).

4.5.3 Backfilling

Backfilling, as defined by the WFD, refers to a recovery operation where suitable non-hazardous waste is used to reclaim excavated areas or serve engineering purposes in landscaping. In this process, non-waste materials are replaced with appropriate waste to perform specific functions, thereby supporting material recovery (European Parliament and the Council, 2008). In the context of construction, backfilling involves refilling an excavated pit with material to reinforce and support the foundation or other structural components. Importantly, in line with the recovery definition, backfilling should substitute materials that are not considered waste. Consequently, the distinction between reusing excavated soil and backfilling is largely semantic, reflecting a difference within the waste hierarchy (European Commission: Joint Research Centre: Cristóbal García et al., 2023).

4.5.4 Soil Waste Treatment in the EU

In line with the data presented and discussed by the authors in the report, Figure 4-13 illustrates the treatment of the excavated soil fraction (non-hazardous) of CDW in the Member States in 2020. It is important to note that the authors mentioned the need for further data quality assessment and highlighted some limitations. Please refer to the report for details (European Commission: Joint Research Centre: Cristóbal García et al., 2023). As shown in Figure 4-13 below and as stated by the authors, there is no dominant treatment option at the EU level. For instance, the Netherlands, Lithuania, Italy, Cyprus, Bulgaria, and Denmark indicated recycling rates exceeding 80%, while Malta has 100% disposal, and Latvia, Slovenia, and Ireland 100% backfilling. Moreover, countries like Finland (93%), Austria (66%), and Croatia (46%) exhibit high disposal rates for this fraction. The authors calculated the average recovery rate for soils in the EU in 2020 to be 76% (European Commission: Directorate-General for Environment: Flexman et al., 2024; European Commission: Joint Research Centre: Cristóbal García et al., 2023).

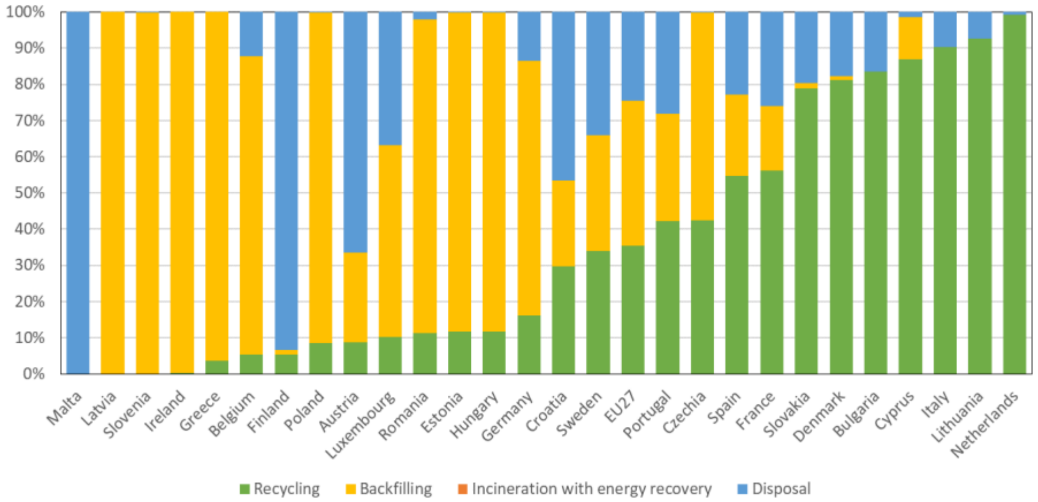


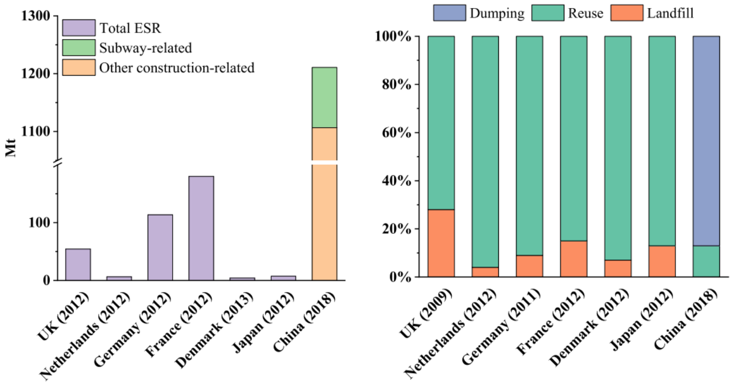
Figure 4-13. Treatment of the excavated soil fraction of CDW in the Member States in 2020, from (European Commission: Joint Research Centre, 2023).

In Sweden, the treatment options for the excavated soil fraction are almost evenly distributed, with the recycling rate at approximately 34%, 33% allocated to backfilling, and 33% to disposal, as seen in Figure 4-13 above.

According to data reported by the Member States and the available techno-scientific literature presented in the report, the overall rate for the excavated soil fraction is distributed as follows: 35% for recycling, 40% for backfilling, and 25% for landfilling (European Commission: Directorate-General for Environment: Flexman et al., 2024; European Commission: Joint Research Centre: Cristóbal García et al., 2023).

4.5.5 Excavated soil and rock treatment in China

The study by (Zhang, Duan, et al., 2020) examined the generation, composition, flows, and potential impacts of ESR in China concerning the construction of a large subway system. The data presented estimated that from 1965 to 2018, the average annual generation of subway-related ESR was 8.9 ± 0.6 million m^3, and it reached 79 ± 4 million m^3 in 2018, indicating that the subway-related ESR generation in China is roughly equivalent to the total ESR of Germany; 104 Mt in China compared to 114 Mt in Germany (Deloitte, 2015). Despite the large volume, nearly 87% of the total generation of ESR is disposed of in dumping sites or unregulated landfills, while only a small portion is reused (backfilling), mostly miscellaneous fill (90%) and sandy clay (8%) (Zhang, Duan, et al., 2020). However, the study found a significant potential for recycling excavated sand and gravel, given that the composition of ESR in China is primarily made up of a large proportion of high-quality sand and gravel throughout the country. This aligns with the earlier statement by (Cristóbal et al., 2024), which suggests that the recycling rate primarily depends on the composition of ESR, particularly its particle size distribution. As shown in Figure 4-14 below, the ESR reuse rate in China is notably low at just 13% when compared to some high-income countries. The authors attributed this to the lack of a mature management system and the lower recycling awareness among governments, in contrast to the situation in high-income countries.



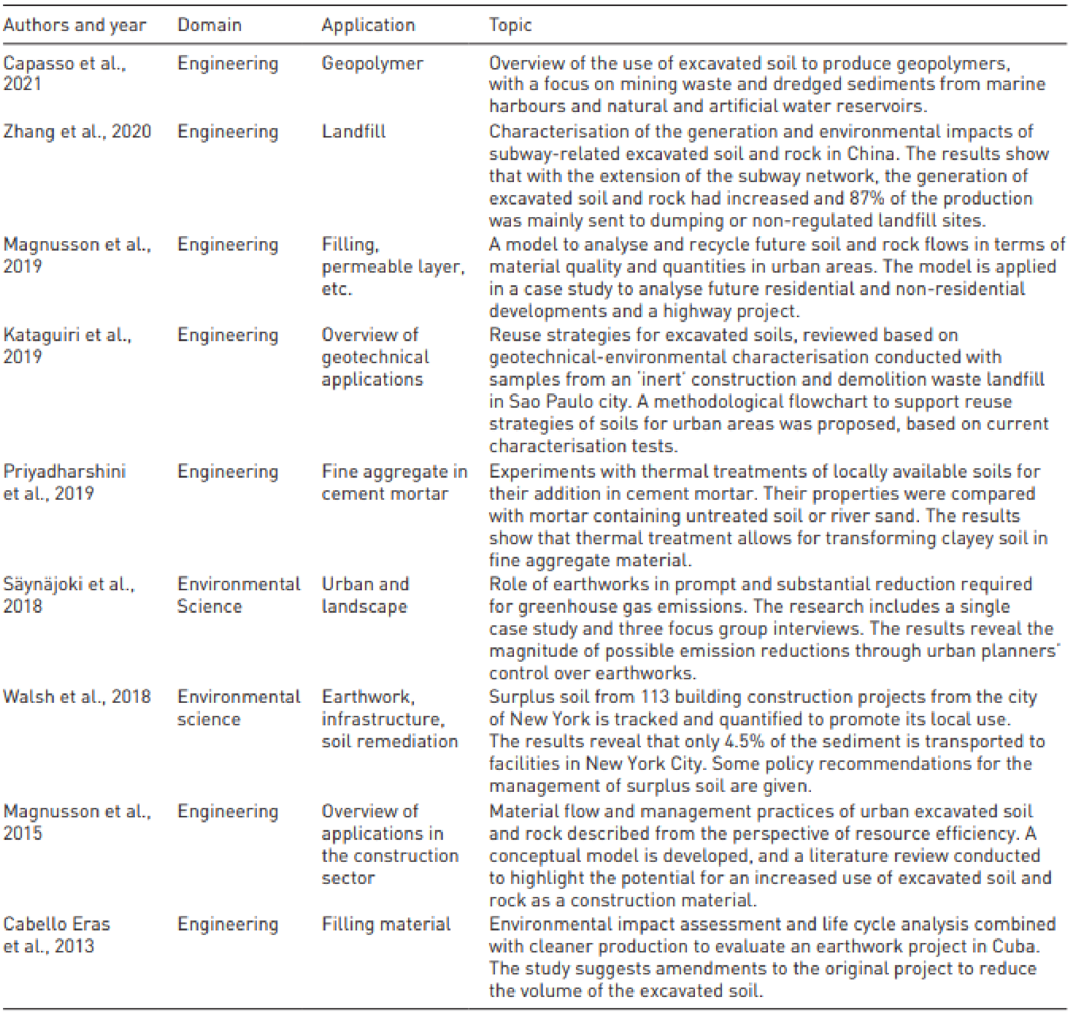
(a) Generation (b) Landfill and dumping rates

Figure 4-14. Construction soil waste generation and landfilling rates: a comparison between China and some developed countries, from (Zhang, Duan, et al., 2020).

*Here dumping means randomly dumped or disposed of in unregulated landfills because there is rarely any regulated landfill for construction soil waste in China

4.5.6 Potential use of excavated soil for construction purposes in urban areas

(Scialpi & Perrotti, 2022) performed a literature review on using urban biowaste and excavated soil in the construction sector. When it comes to the application of excavated soil in urban areas for construction purposes, the findings from the study can be seen in Figure 4-15 below. According to (Magnusson et al., 2019) excavated rock, sand, gravel, and till are relatively easy to prepare for recycling as filling material, permeable layer, or base layer. Based on the geotechnical properties of the soil, (Kataguiri et al., 2019) suggest that excavated soil can be reused in applications where the material is confined, such as trench backfill and walls with reinforced soil. They also concluded that the soil from their study is suitable for reuse in drainage applications. In contrast, the mixture of soil and other CDW can be reused for paving layers. Moreover, (Kataguiri et al., 2019) highlight other potential uses identified in the literature, including its application as a replacement for vegetation covers. Additionally, excavated soil has been explored for use in the production of geopolymer-based materials, primarily in relation to mining waste and dredged marine sediments (Capasso et al., 2021) or as an additive in cement mortar (Priyadharshini et al., 2019). The study concluded that thermal treatment effectively transforms clayey soil, including high-plasticity soil, into a suitable fine aggregate material for use in cement mortar (Priyadharshini et al., 2019).



Authors and year	Domain	Application	Topic
Capasso et al., 2021	Engineering	Geopolymer	Overview of the use of excavated soil to produce geopolymers, with a focus on mining waste and dredged sediments from marine harbours and natural and artificial water reservoirs.
Zhang et al., 2020	Engineering	Landfill	Characterisation of the generation and environmental impacts of subway-related excavated soil and rock in China. The results show that with the extension of the subway network, the generation of excavated soil and rock had increased and 87% of the production was mainly sent to dumping or non-regulated landfill sites.
Magnusson et al., 2019	Engineering	Filling, permeable layer, etc.	A model to analyse and recycle future soil and rock flows in terms of material quality and quantities in urban areas. The model is applied in a case study to analyse future residential and non-residential developments and a highway project.
Kataguiri et al., 2019	Engineering	Overview of geotechnical applications	Reuse strategies for excavated soils, reviewed based on geotechnical-environmental characterisation conducted with samples from an 'inert' construction and demolition waste landfill in Sao Paulo city. A methodological flowchart to support reuse strategies of soils for urban areas was proposed, based on current characterisation tests.
Priyadharshini et al., 2019	Engineering	Fine aggregate in cement mortar	Experiments with thermal treatments of locally available soils for their addition in cement mortar. Their properties were compared with mortar containing untreated soil or river sand. The results show that thermal treatment allows for transforming clayey soil in fine aggregate material.
Säynäjoki et al., 2018	Environmental Science	Urban and landscape	Role of earthworks in prompt and substantial reduction required for greenhouse gas emissions. The research includes a single case study and three focus group interviews. The results reveal the magnitude of possible emission reductions through urban planners' control over earthworks.
Walsh et al., 2018	Environmental science	Earthwork, infrastructure, soil remediation	Surplus soil from 113 building construction projects from the city of New York is tracked and quantified to promote its local use. The results reveal that only 4.5% of the sediment is transported to facilities in New York City. Some policy recommendations for the management of surplus soil are given.
Magnusson et al., 2015	Engineering	Overview of applications in the construction sector	Material flow and management practices of urban excavated soil and rock described from the perspective of resource efficiency. A conceptual model is developed, and a literature review conducted to highlight the potential for an increased use of excavated soil and rock as a construction material.
Cabello Eras et al., 2013	Engineering	Filling material	Environmental impact assessment and life cycle analysis combined with cleaner production to evaluate an earthwork project in Cuba. The study suggests amendments to the original project to reduce the volume of the excavated soil.

Figure 4-15. The literature review results: the use of excavated soil in construction purposes, from (Scialpi & Perrotti, 2022).

While not covered in the literature review by (Scialpi & Perrotti, 2022), other research highlights additional applications for ESR, including the production of recycled bricks made by mixing recycled clay from ESR with other materials (Zhang, Zhang, et al., 2020). Additionally, the production of cement-treated base materials is possible by using recycled crushed aggregates (Xu et al., 2022), as seen in Figure 4-10, or concrete blocks where natural aggregates are substituted with excavated soil and or recycled concrete aggregates (Luo et al., 2022).

Furthermore, the study's authors (Scialpi & Perrotti, 2022) also suggest that combining urban biowaste with excavated soil could present valuable opportunities for advancing recycling strategies and waste management in Europe. The fiber-rich organic components of biowaste have the potential to improve the thermal, acoustic, and mechanical properties of soil-based products, providing a sustainable alternative to incineration and landfilling. This approach could also help lower energy consumption and reduce greenhouse gas emissions (Scialpi & Perrotti, 2022).

5 The Concept of Urban Metabolism

The origins of the urban metabolism (UM) concept have roots in μεταβολικός (metabolikós) biological concept, developed in the nineteenth century by Theodor Schwann, a so-called neologism (Restrepo & Morales-Pinzón, 2018), Figure 5-1. However, two centuries earlier, the Italian scientist Santorio Santorio conducted the first study of human metabolism, see Figure 5-1, spanning three decades. His research focused on measuring the mass ingested by a person relative to their body weight, as well as the mass expelled through feces and urine, which contributed to a new awareness of human bodies (Brunner & Rechberger, 2005). A century later, urban planners began viewing cities as systems that function like biological organisms, adopting the city-as-human-body metaphor. In this framework, terms like “vein” and “artery” referred to one-way roads, while expressions such as “urban heart” distinguished the functional centers of cities (Sennett, 1996). This comparison to living organisms has made UM an effective strategy for better understanding a city's ecological footprint and working toward its sustainability (Sanches & Bento, 2020).

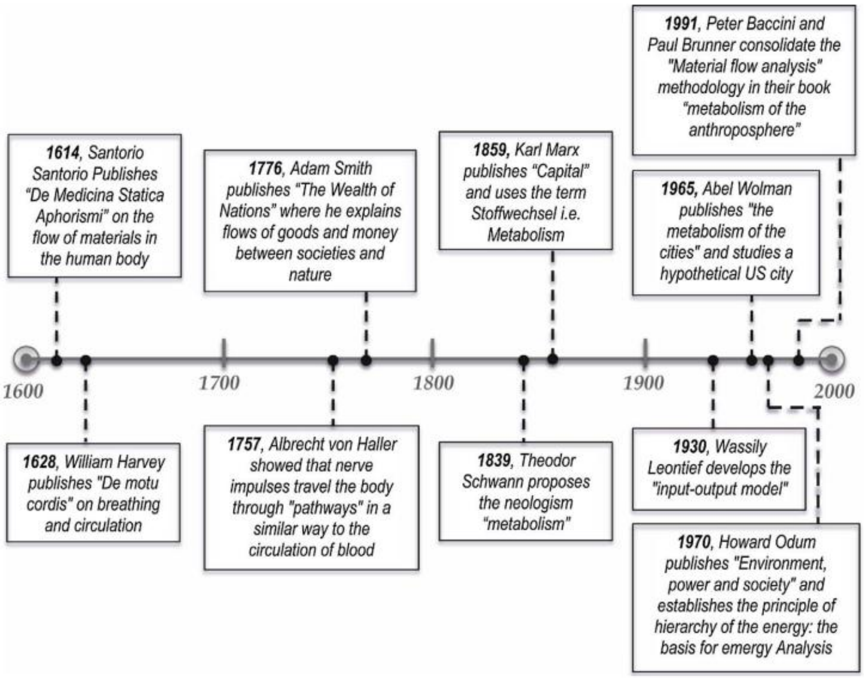


Figure 5-1. Timeline of relevant events in the emergence of urban metabolism, from (Restrepo & Morales-Pinzón, 2018).

Karl Marx was the first to discuss social metabolism, referring to the flows between the economic system and the natural world, highlighting the distinction between ecological and economic exchange, Figure 5-1 and Figure 5-2. However, it wasn’t until the 1960s that Abel Wolman introduced the concept of UM (Brunner & Rechberger, 2005), as shown in Figure 5-1 and Figure 5-2. Wolman defined UM as “all the materials and commodities needed to sustain the city’s inhabitants at home, at work, and at play” (Wolman, 1965). (Kennedy et al., 2007) provided a widely accepted definition of UM, Figure 5-2, as "the sum total of the technical and socio-economic processes that occur in cities, leading to growth, energy production, and waste elimination", which laid the foundation for the further development of UM studies (Restrepo & Morales-Pinzón, 2018).

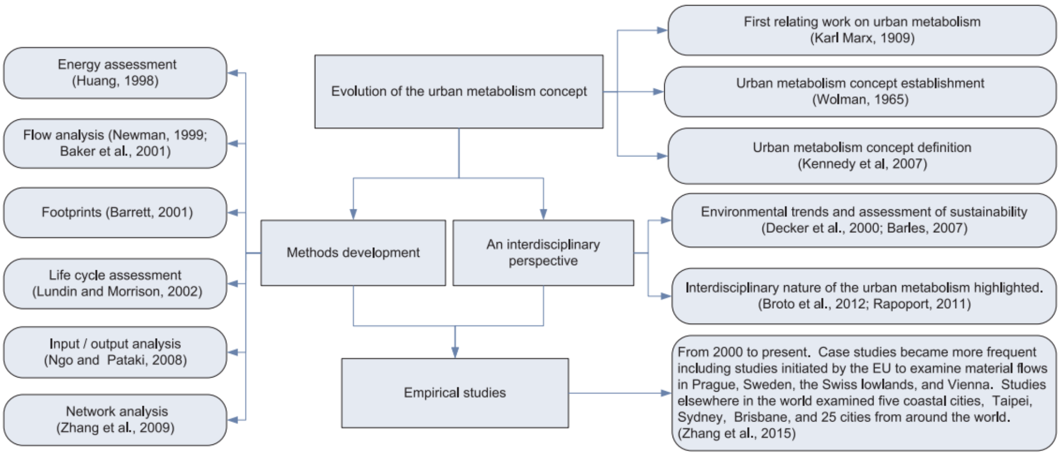


Figure 5-2. Roadmap for the evolution of urban metabolism studies, from (Cui, 2018).

There are two main schools of thought in UM (Cui, 2018). One, represented by (Odum, 1983) is based on energy equivalence, while the other, which is more widely used today, focuses on the metabolism analysis of the flow of material resources, water, nutrients, and other (Shen & Ma, 2015). The Odum school applied biophysical value theory to assess economic and ecological systems (Huang, 1998) quantifying the energy equivalence of various energy forms (fuel, electricity, solar energy) (Cui, 2018). However, the approach faced limitations in practical applications, such as issues with conversion and calculation, hindering its broader use and development, although, from a sustainable development perspective has some advantages (Cui, 2018). By contrast, the MFA approach considers units, making the method more comprehensible, particularly for governments and policymakers (Cui, 2018).

5.1 Challenges and Opportunities of Urban Metabolism

In general, the UM field has some challenges to overcome, including the need to integrate with other approaches focused on identifying opportunities for resource efficiency, as it primarily provides a retrospective analysis of resource stocks and flows (Derrible et al., 2021). According to (John et al., 2019), two-thirds of 221 UM studies followed a problem-oriented approach, focusing on defining the metabolism of the system and understanding risks, rather than aiming to address specific challenges. There is a need to broaden the scope of UM to guide design, optimization, and decision-making (Derrible et al., 2021). However, there are opportunities to enhance the UM field, such as the availability of new data sources that enable more detailed UM analysis, operating at finer temporal resolutions, being spatially explicit, and integrating relevant information from various sources (Derrible et al., 2021). Additionally, mapping resource flows for a more spatially explicit UM analysis will offer insights into the direction and distribution of internal flows within the city (Derrible et al., 2021). Furthermore, integrating data from various sources could give analysts a deeper understanding of the interdependencies and relationships between different resource flows. For example, linking water consumption with energy use or connecting resource demand to urban activities could support more holistic policy decisions and integrated resource management (Derrible et al., 2021). Next, there is potential to advance UM analysis from a descriptive approach to a more prescriptive one by studying resource flows through cities in simulations. This allows analysts to test possible interventions, see (Derrible et al., 2021), for more details. Coupling UM with sustainable urban planning and design enables stakeholders to explore impact mitigation pathways and consider strategies to achieve sustainable urban renewal and growth (Derrible et al., 2021).

6 Urban Metabolism, Circular Economy, Doughnut Economy, and Sustainability

In prehistoric times, human material metabolism, encompassing the flow of materials and energy required for basic needs such as food, air, and shelter, was closely aligned with physiological metabolism, meaning only those essential needs had to be met (Brunner & Rechberger, 2005). In contrast, modern humans have a material turnover 10 to 20 times greater (Brunner & Rechberger, 2005), see Figure 6-1. Today, a smaller portion of material turnover goes toward basic needs like food and breathing, with much more focused on activities like cleaning, housing, transportation, and communication, which require a wide range of products and materials, leading to significant resource consumption, which is directly related to economic growth (Brunner & Rechberger, 2005; Sanches & Bento, 2020).

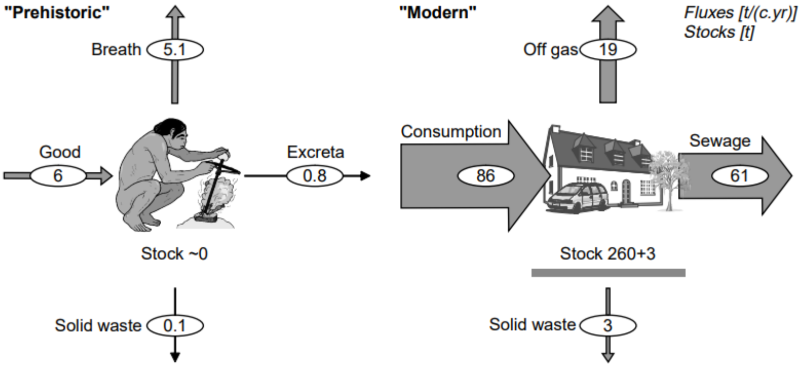


Figure 6-1. Material turnover in modern humans compared to prehistoric humans, from (Brunner & Rechberger, 2005).

One way to minimize resource consumption and separate economic growth from material growth is by adopting UM and CE (Brunner & Rechberger, 2005; Sanches & Bento, 2020). Namely, UM characterizes cities as complex systems that utilize resources and produce waste to sustain their operations, resulting in unsustainable consumption patterns (Whetstone et al., 2020). To mitigate the ecological footprints of urban areas, UM aids in identifying and mapping resource flows within cities and serves as a valuable framework for resource consumption analysis, strategic planning, and decision-making (Sanches & Bento, 2020; Teixeira & Bento, 2018). Moreover, by adopting the UM framework, cities can shift from a linear to a networked and cyclical perspective, facilitating the conversion of waste into usable inputs and reducing reliance on external resources (Musango et al., 2017), thus positioning UM as a strategy for shifting from a linear economy to a CE (Sanches & Bento, 2020). The same can be applied to the management of excavated soil, as described later in the text.

Also, as noted by (Derrible et al., 2021) one of the challenges with UM is that it must work alongside other approaches to identify opportunities for resource efficiency, suggesting that coupling with CE could offer a potential solution.

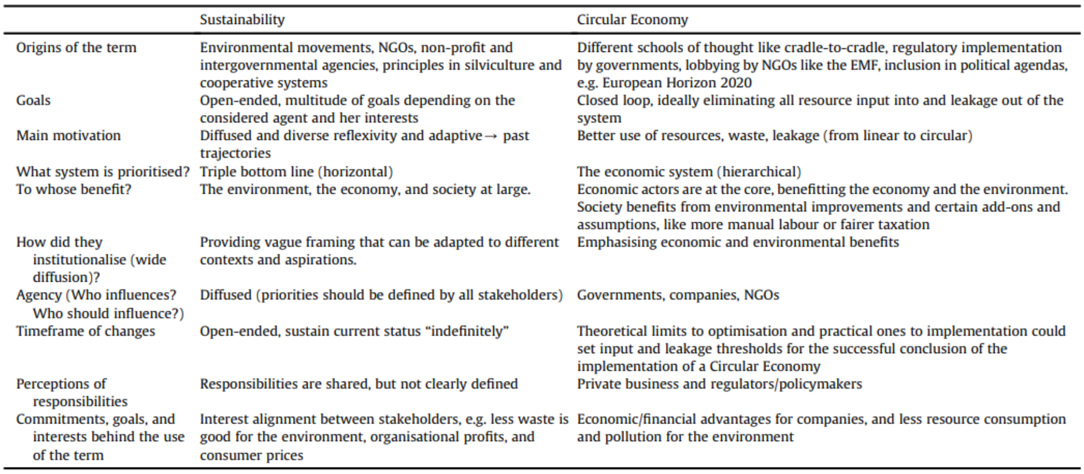
Furthermore, connecting UM to policy strategies is essential for assessing and enhancing urban sustainability, as it offers a deeper insight into the complexity of cities and serves as the basis for more informed and sustainable development decisions through an interdisciplinary approach (Sanches & Bento, 2020). More precisely, UM literature offers valuable insights into cities' contributions to sustainability, including (1) changes in consumption patterns as urbanization progresses, (2) the biogeochemical cycles of materials and associated pollution issues, (3) simplified elements of UM to guide policymaking and support urban development, and (4) the creation of opportunities and improvement of habitat well-being through efficient resource use and reuse. Therefore, UM research plays a pivotal role in advancing sustainability (Cui, 2018).

Moreover, (Geissdoerfer et al., 2017) conducted a literature review to explore and synthesize the concepts of CE and sustainability, examining their similarities, differences, and relationships. The findings show that both concepts aim to address challenges related to the current state of technology, industrial production, and consumption. They also highlight the importance of aligning environmental and social factors with economic development, with system-wide changes at the core of their approaches (Geissdoerfer et al., 2017). Some of the selected similarities can be seen in Table 6-1 below.

Table 6-1. Selected similarities between sustainability and the CE, from (Geissdoerfer et al., 2017).

Similarities between sustainability and CE
• Intra and intergenerational commitments
• More agency for the multiple and coexisting pathways of development
• Global models
• Integrating non-economic aspects into development
• System change/design and innovation at the core
• Multi-/interdisciplinary research field
• Potential cost, risk, diversification, value co-creation opportunities
• Cooperation of different stakeholders is necessary
• Regulation and incentives as core implementation tools
• Central role of private business, due to resources and capabilities
• Business model innovation as a key to industry transformation
• Technological solutions are important, but often pose implementation problems

Additionally, the authors point out differences between the two concepts, such as their origins, objectives, motivations, system priorities, institutionalization, beneficiaries, timeframes, and perspectives on responsibility. For example, while the CE strives for a closed-loop system that eliminates resource inputs, waste, and emission leaks, the goals of sustainability remain broad and flexible (Geissdoerfer et al., 2017). Various authors highlight a wide range of sustainability goals, which can shift depending on the agents involved and their respective interests (Geissdoerfer et al., 2017). Moreover, sustainability aims to benefit all three dimensions - environmental, economic, and social (Elkington, 1997), while CE is mainly centered on the economic aspect, meaning that the economic system is prioritized (Geissdoerfer et al., 2017). For more details on differences, see Figure 6-2 below. In addition to the points outlined earlier, (Ortiz-de-Montellano et al., 2023) concluded that while the CE primarily focuses on products and materials, the SDGs place greater emphasis on people and the environment.



	Sustainability	Circular Economy
Origins of the term	Environmental movements, NGOs, non-profit and intergovernmental agencies, principles in silviculture and cooperative systems	Different schools of thought like cradle-to-cradle, regulatory implementation by governments, lobbying by NGOs like the EMF, inclusion in political agendas, e.g. European Horizon 2020
Goals	Open-ended, multitude of goals depending on the considered agent and her interests	Closed loop, ideally eliminating all resource input into and leakage out of the system
Main motivation	Diffused and diverse reflexivity and adaptive → past trajectories	Better use of resources, waste, leakage (from linear to circular)
What system is prioritised?	Triple bottom line (horizontal)	The economic system (hierarchical)
To whose benefit?	The environment, the economy, and society at large.	Economic actors are at the core, benefitting the economy and the environment. Society benefits from environmental improvements and certain add-ons and assumptions, like more manual labour or fairer taxation
How did they institutionalise (wide diffusion)?	Providing vague framing that can be adapted to different contexts and aspirations.	Emphasising economic and environmental benefits
Agency (Who influences? Who should influence?)	Diffused (priorities should be defined by all stakeholders)	Governments, companies, NGOs
Timeframe of changes	Open-ended, sustain current status "indefinitely"	Theoretical limits to optimisation and practical ones to implementation could set input and leakage thresholds for the successful conclusion of the implementation of a Circular Economy
Perceptions of responsibilities	Responsibilities are shared, but not clearly defined	Private business and regulators/policymakers
Commitments, goals, and interests behind the use of the term	Interest alignment between stakeholders, e.g. less waste is good for the environment, organisational profits, and consumer prices	Economic/financial advantages for companies, and less resource consumption and pollution for the environment

Figure 6-2. Selected differences between sustainability and the CE, from (Geissdoerfer et al., 2017).

Finally, regarding the relationship between CE and sustainability, the authors concluded that it can be characterized by conditional, beneficial, and trade-off relationships, based on the performed literature review (Geissdoerfer et al., 2017). Specifically, the conditional relationship suggests that CE may serve as one of the key solutions, or even the primary solution, for achieving a sustainable system. However, it can also be a necessary, but not sufficient, condition for sustainability. The beneficial relationship highlights how CE contributes positively to sustainability, either as a solution on its own or as one of several approaches to fostering a more sustainable system. The trade-off involves a degree of relationship, where a certain level of sustainability is achieved, with other concepts being either more or less sustainable. It also includes a cost-benefit relationship, where the costs and benefits are weighed in terms of sustainability. Additionally, there is a selective relationship, which promotes certain aspects of sustainability while neglecting others (Geissdoerfer et al., 2017).

In terms of CE contributions to the SDGs, (Ortiz-de-Montellano et al., 2023) examined the potential impact of 27 CE strategies, adapted from (Garcia-Saravia Ortiz-de-Montellano & van der Meer, 2022), on all 17 SDGs. To link these strategies with the SDGs, the authors identified seven key pathways: 1) Reduced, traceable extraction; 2) Regenerative, biobased production; 3) Human-inclusive industries; 4) Shareable longevity; 5) Consumers at the center, not consumerism; 6) Clean and effective end-of-life processes; and 7) Reduced and clean energy and transport. Their findings suggest that while CE strategies can contribute to all SDGs, they have the greatest impact on SDGs 8, 12, and 13, and the least impact on SDGs 4, 5, 10, and 16. Pathways 2, 4, and 6 were identified as the most influential, accounting for 66% of the potential contributions to the SDGs. The "use, reuse, and re-sell" strategy is the most effective approach for achieving the SDGs, influencing 14 out of the 17 goals (Ortiz-de-Montellano et al., 2023). The "reduce" and "repair, refurbish, and remanufacture" strategies also demonstrate significant potential for impacting the SDGs. On the other hand, “recycling” was rated as the least effective strategy in achieving the SDGs (Ortiz-de-Montellano et al., 2023). However, it is important to note that, as mentioned earlier, the definition of CE varies, and there is currently no universally accepted definition. With this in mind, the impacts of CE strategies on SDGs, as described above, should be interpreted in the context of the CE strategies outlined by authors (Ortiz-de-Montellano et al., 2023), which differ from the 9R framework defined by (Kirchherr et al., 2017). Nevertheless, it is interesting to explore which CE strategy has the greatest impact on the SDGs and how this can be connected to the CE strategies for managing excavated soil. As previously mentioned, the identified CE strategies for managing excavated soil include reuse, recycling, and backfilling/recovery. This is particularly interesting because, although authors (Ortiz-de-Montellano et al., 2023) have noted that recycling contributes least to SDGs, it plays a significant role in the management of excavated soil. Also, one of the strategies identified by authors within the "reduce" category, please refer to (Ortiz-de-Montellano et al., 2023) for more details, is enabling material traceability, which is considered a key approach for improving current practices in the management of excavated soil, as discussed in Chapter 9. However, as mentioned earlier, there is variability in how CE strategies are interpreted, which can influence their application and effectiveness in different contexts.

Furthermore, the Doughnut model can provide valuable guidance for managing excavated soil by promoting practices that strike a balance between ecological sustainability and socio-economic equity. Excavated soil is an inevitable byproduct of various construction projects, including buildings, housing developments, and infrastructure projects such as roads or railways, all of which demand substantial energy and water consumption (Llatas, 2011). This excavation process contributes to significant environmental impacts, as it often involves transportation, processing, and disposal of large volumes of soil, further depleting resources and exacerbating the carbon footprint. At the same time, it is crucial to ensure that the social foundation, when considering the Doughnut, is not compromised, meaning that essential needs, such as housing, are met for all people.

To minimize these environmental impacts, thus staying within planetary boundaries, it is essential to adopt a more circular approach, as outlined in the Section 4.5. This approach emphasizes the reuse of excavated soil, reducing the need for new raw materials and minimizing the ecological impact of extraction and transportation. By reusing soil, it is possible to prevent soil degradation, erosion, and biodiversity loss that may result from excessive excavation (Ding et al., 2016). Moreover, the reuse or recycling of excavated soil helps reduce transportation distances, thereby lowering emissions associated with material movement (Hale et al., 2021; Rugani & Petucco, 2025; Wang et al., 2024). Effective management also ensures that excavated soil is not unnecessarily sent to landfills, directly supporting SDG 11, which emphasizes that sending clean excavated soil to landfill sites is an unsustainable practice (Hale et al., 2021).

From a social perspective, reusing excavated soil in construction projects can lower costs (Hale et al., 2021) and provide more affordable resources, particularly in areas where soil is scarce or expensive to import. By implementing circular soil management practices, the creation of social benefits emerges, such as job opportunities in soil processing, transportation, and environmental monitoring. Proper management of contaminated soil further safeguards public health by preventing hazardous materials from impacting local communities, thereby promoting equitable access to a healthy environment, in line with the social foundations of the Doughnut model.

Overall, it can be stated that the concepts of UM, CE, and Doughnut should be viewed as interconnected frameworks for sustainability. Together, they provide a comprehensive approach to fostering sustainable development, as discussed earlier, each contributing unique insights and strategies to support a more balanced and resilient future. This integrated perspective can be effectively applied to the management of excavated soil, promoting a more balanced, resilient, and resource-efficient approach to construction and infrastructure projects.

7 Evaluation methods

7.1 Material flow analysis

(Derrible et al., 2021) state that the primary objective of UM is "to quantify the inflows, outflows, and accumulation of resources in a city." In this regard, various resources and energy imported, consumed, stored, or exported daily within urban environments can include water, electricity, petrol, natural gas, food, concrete, and asphalt (Derrible et al., 2021). Alternatively, they can be defined in terms of chemically specified substances (e.g., carbon or CO_2) and natural or technical materials (e.g., coal, wood) (Bringezu & Moriguchi, 2002). The principal methodology for quantifying these material flows is MFA, which examines the throughput of process chains, including extraction, chemical transformation, manufacturing, consumption, recycling, and disposal (Bringezu & Moriguchi, 2002). According to (Brunner & Rechberger, 2005) MFA is a method used to systematically assess the flows and stocks of materials within a defined system over time and space. It tracks the sources, pathways, and final destinations of materials. The main terminology used in MFA is summarized in Table 7-1, whereas the key symbols commonly used in MFA diagrams are shown in Figure 7-1 below.

Table 7-1. Description of terminology used in MFA, from (Brunner & Rechberger, 2005).

Term	Definition
Material	Substances and goods
Goods	Substances or mixtures of substances with economic values assigned by markets
Process	Transport, transformation, or storage of materials. Processes are linked by flows/fluxes.
Stocks	Material reservoirs (mass) within the analyzed system
Flows/Fluxes	Mass per time (flows) or mass per time and cross section (fluxes). Flows/fluxes across system boundaries are called imports or exports. Flows/fluxes of materials entering a process are named inputs, while those exiting are called outputs.
System	Set of material flows, stocks, and processes within a defined boundary (e.g., a region, a private household, a factory, a farm, etc.)

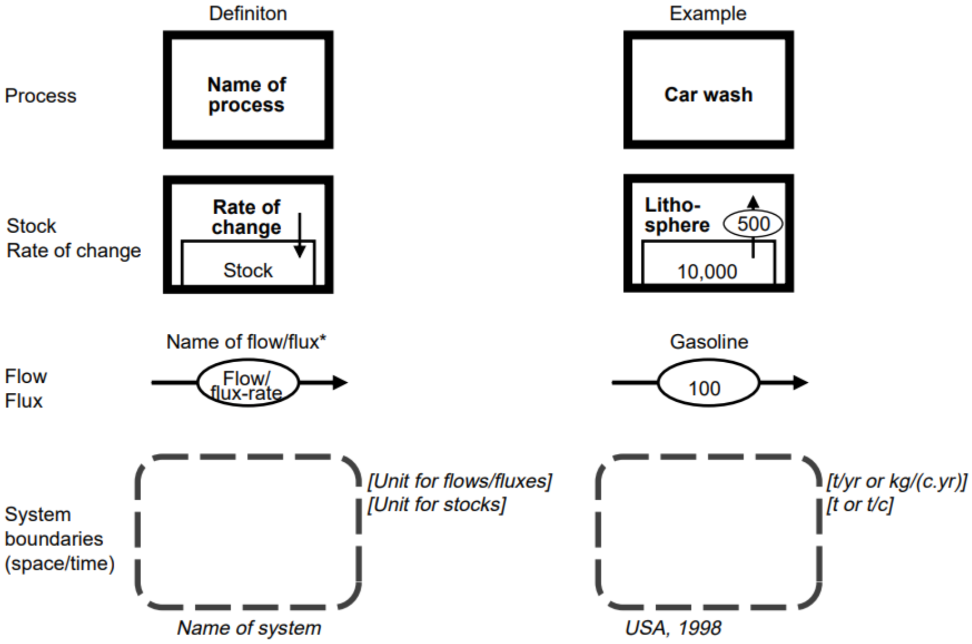


Figure 7-1. Main symbols used in MFA diagrams, from (Brunner & Rechberger, 2005).

An MFA generally follows a series of steps: initially, the problem is defined, and specific goals are established. Then, relevant substances, system boundaries, processes, and goods are identified. The next step involves assessing the mass flows of goods and the concentrations of substances within those flows. Following that, substance flows, and stocks are calculated, with attention given to any uncertainties. Lastly, the results are presented in a manner that visualizes conclusions and aids in making informed, goal-driven decisions (Brunner & Rechberger, 2005). The illustration of the described process is shown in Figure 7-2 below. It is important to highlight that MFA is an iterative process, where the selection of elements (such as substances, processes, goods, and boundaries) and the accuracy of the data must be continually assessed in alignment with the study's objectives (Brunner & Rechberger, 2005).

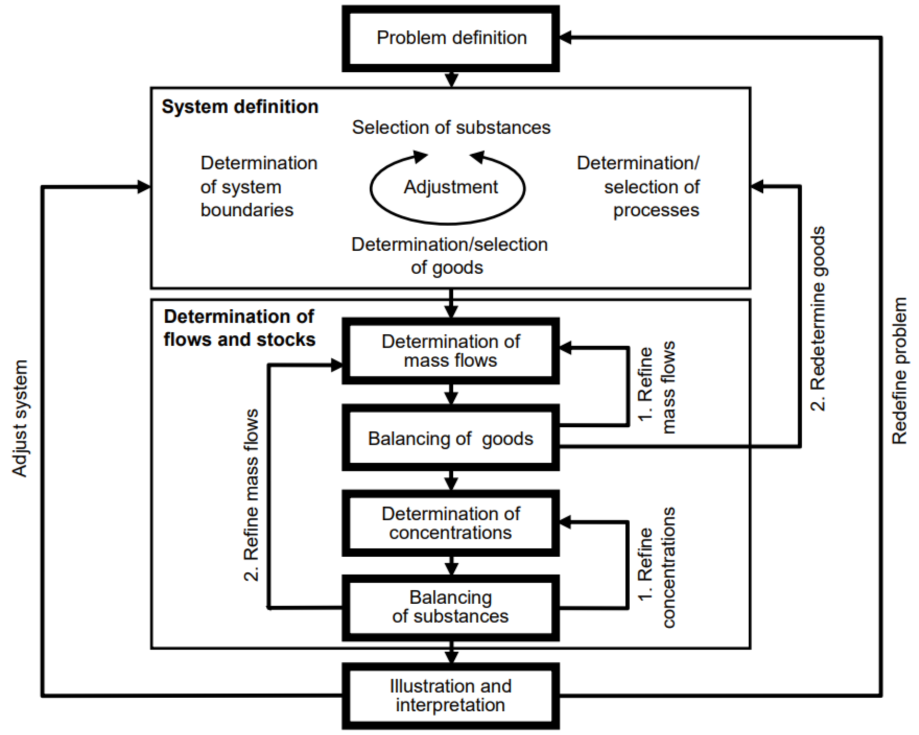


Figure 7-2. Procedures for MFA, from (Brunner & Rechberger, 2005).

Along with the fundamental terms discussed, the additional term *activity* plays a key role in assessing and designing human-made processes and systems. An activity is a system made up of the flows, stocks, and processes of materials needed to satisfy a specific human need, such as food, shelter, or transportation. By examining the material flows within an activity, potential challenges, like environmental impacts and resource depletion, can be identified early on (Brunner & Rechberger, 2005). The basic activities defined according to (Brunner & Rechberger, 2005) are: *to nourish, to clean, to reside and work, and to transport and communicate*. The activity that can be to some extent relevant to the excavated soil is *to reside and work*, with a focus on constructing residential units rather than infrastructure projects, which are more pertinent to this work. The Table 7-2 below outlines the subprocesses involved in building construction, along with their respective input and output goods.

Table 7-2. Subprocesses for "Building construction", from (Brunner & Rechberger, 2005).

Process	Subprocess	Inputs	Outputs
Building construction	Concrete production, steel and metal production, quarry, lumber mill, energy supply	Gravel, sand, stone, limestone, marl, metal ores, wood, fuels, water, air	Buildings, construction and demolition waste, wastewater, off-gas

However, since excavated soil is classified as CDW (European Commission, 2000), it is relevant to consider the associated processes and goods related to the activity *to reside and work*, as illustrated in Figure 7-3 below.

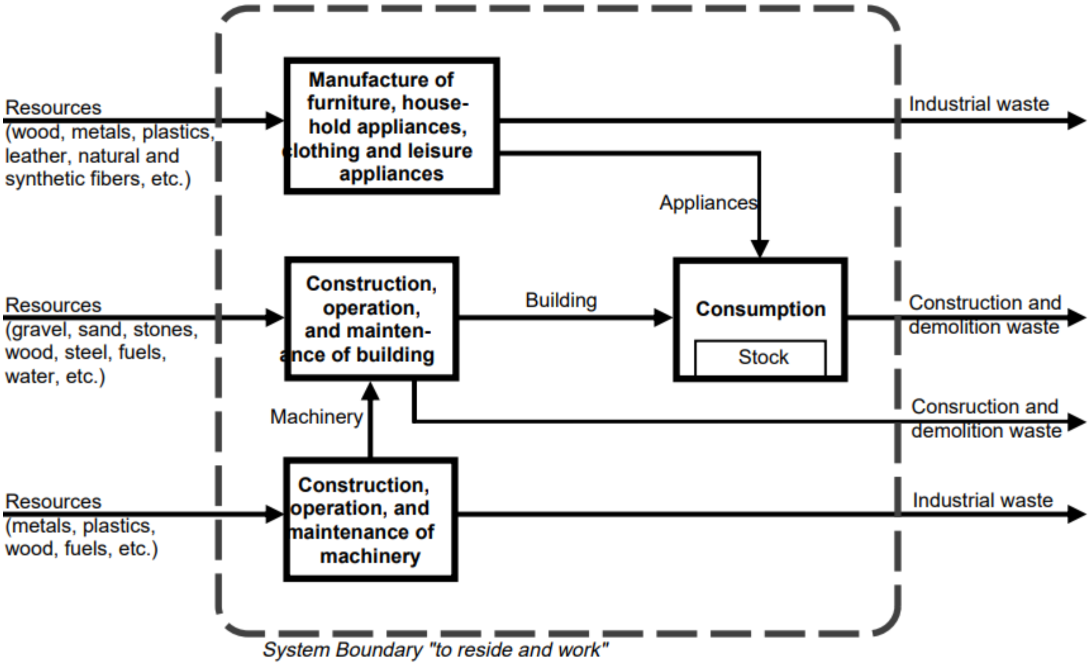


Figure 7-3. Relevant processes and goods associated with the activity to reside and work, from (Brunner & Rechberger, 2005).

The application of the MFA can be seen in numerous environmental engineering and management tasks, such as creating environmental impact assessments, remediating hazardous waste sites, designing air pollution control measures, managing nutrients in watersheds, planning soil monitoring programs, and overseeing sewage sludge management. Each of these activities demands a comprehensive understanding of the material flows and stocks within both the environment and the human-made systems (Brunner & Rechberger, 2005). Additionally, MFA serves as a crucial tool in industrial ecology, where its results can highlight key processes throughout the material lifecycle, identify significant material stocks in both the economy and environment, pinpoint environmental losses, and track internal recycling processes (Brunner & Rechberger, 2005). However, the limitation of MFA lies in its insufficiency for assessing or supporting engineering or management measures on its own (Brunner & Rechberger, 2005).

In addition, the term *substance flow analysis (SFA)* can be used occasionally, as some authors do not differentiate between goods, materials, and substances in the way described here, and based on (Brunner & Rechberger, 2005). Furthermore, "*economy-wide*" MFA offers comprehensive records of the total material inputs into national economies, the changes in material stock within the economic system, and the material outputs to other economies or the environment, as shown in Figure 7-4 (Krausmann et al., 2015). Moreover, *Material and energy flow analysis* (MEFA) includes the flow of energy alongside material flows (Derrible et al., 2021). On top of that, *Material flow cost accounting* (MFCA) focuses on the internalized costs of material flows to minimize waste and enhance resource efficiency (Schaltegger & Zvezdov, 2015). By quantifying both physical and monetary flows and stocks within processes, MFCA integrates environmental and economic factors, promoting eco-efficiency by minimizing negative environmental impacts and boosting productivity

(Kokubu & Kitada, 2015; Zhou et al., 2017), thereby supporting sustainable development decision-making processes (Zeng et al., 2021).

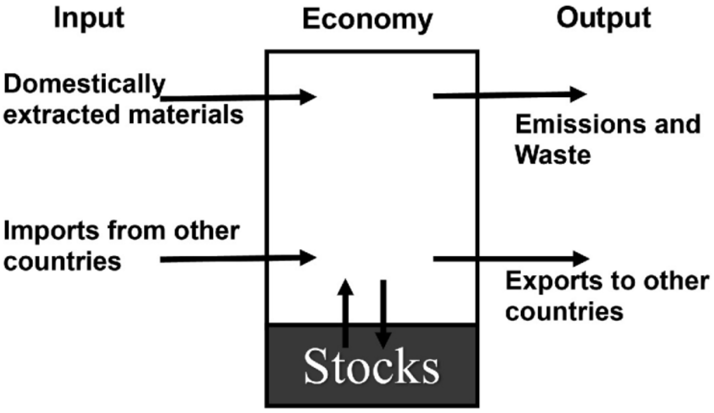


Figure 7-4. General framework of economy-wide MFA. After (Derrible et al., 2021)(Adopted and modified from (EUROSTAT, 2001) and (Krausmann et al., 2015)).

A typical economy-wide MFA approach categorizes materials into four main groups: biomass, metal ores, non-metallic minerals, and fossil energy carriers, among 70 material groups (Derrible et al., 2021). There are three methods for measuring flows: bottom-up, top-down, and hybrid approaches. The bottom-up method is generally preferred as it involves investigating data about flows individually, often by contacting local authorities such as water, gas, and electricity utility companies, thus providing detailed information about the city itself (Derrible et al., 2021). However, collecting this data can be challenging due to local companies' reluctance to share information or a lack of data. Additionally, this process can be time-consuming. The top-down approach utilizes economic input-output data, typically at the country scale, and then disaggregates it to the city scale, sometimes making it easier to apply. It also relies on international datasets, useful for making time-series assessments to track progress over time (Derrible et al., 2021). Hybrid methods may include LCA, which provides quantities of all materials used in commodity production, environmentally extended input-output models, or a combination of both, important for estimating consumption-based indicators such as the material footprint of an economy (Derrible et al., 2021).

7.1.1 Material flow analysis in mass management

The Optimass project, see later in the Subsection 8.2.4, demonstrates the application of MFA within mass management and its role in promoting more circular and sustainable practices. To analyze future soil and rock flows in terms of material quality and quantities, see Figure 7-5, the Optimass model was evaluated with two different scenarios focusing on the geotechnical properties and quantities generated and required within industrial, residential, and highway construction projects in the Södertörn Region, an area south of Stockholm (Magnusson et al., 2019). One scenario illustrates business as usual (BAU), while the other focuses on material coordination at strategically placed recycling sites, positioned between various developments to reduce transportation distances, Figure 7-6.

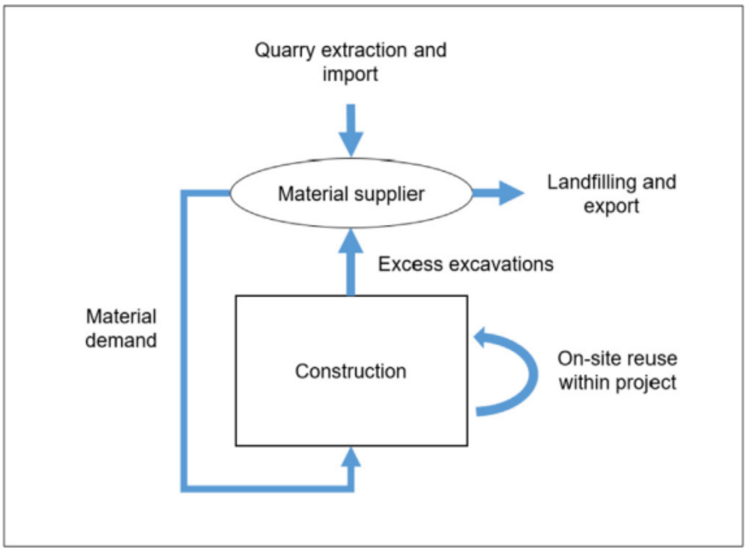


Figure 7-5. Conceptual flow diagram for soil and rock materials within the study area, from (Magnusson et al., 2019).

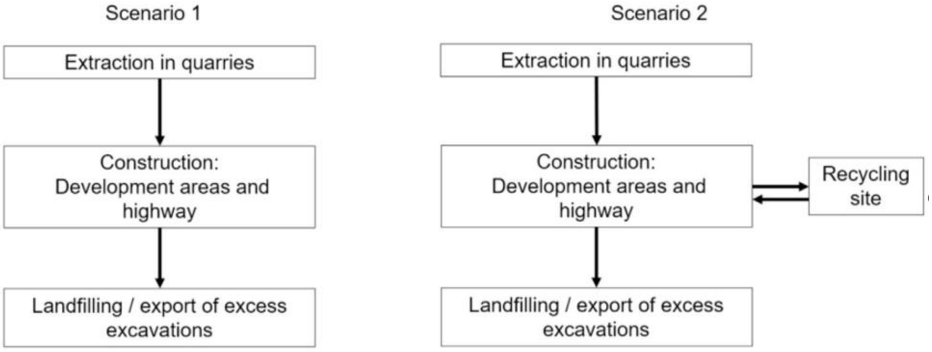


Figure 7-6. The system studied in Scenario 1, Business as Usual, and Scenario 2, material coordination, from (Magnusson et al., 2019).

The study region was divided into four areas, and the future material balance for 2020 to 2030 was analyzed, with the resulting model of estimated soil and rock material flows shown in Figure 7-7. Excavated rock, sand, gravel, and till are intended for filling material, permeable layers for buildings, and base layers for roads (Magnusson et al., 2019). The excess soil and rock materials transported from construction developments are estimated at 8.93 million m^3, while the remaining material demand is approximately 3.88 million m^3, or around 43% of the excess material. A substantial amount of the excavated material is associated with highway construction, but the largest portion, 78% of the total excess excavation volume, comes from residential and non-residential development areas (Magnusson et al., 2019).

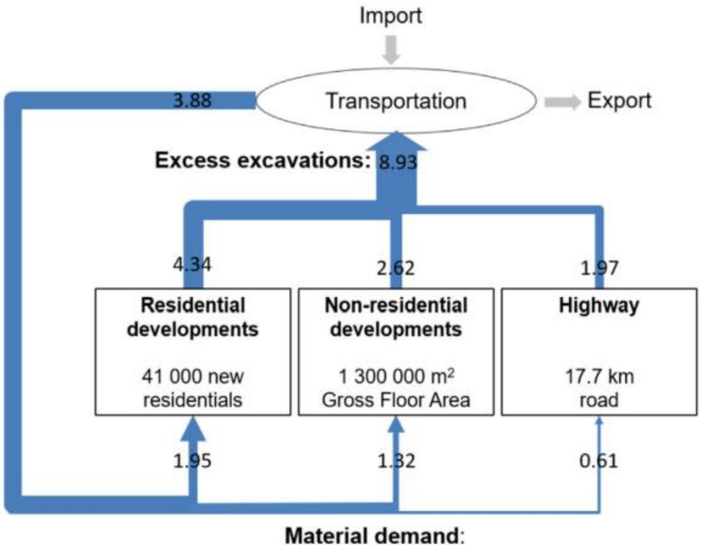


Figure 7-7. Model results: bulk volumes of soil and rock material flows (million m^3) in the region due to construction activities in the studied area, year 2020-2030, from (Magnusson et al., 2019).

Regarding environmental indicators, both scenarios were assessed by examining material efficiency (m^3 of recycled material), transportation demands (kilometers), and GHG from transport activities (tons of CO_2 equivalents), including the loading and movement of materials (Magnusson et al., 2019). The scenario analysis indicates that strategically placing recycling sites for material coordination could minimize soil and rock transportation needs, reducing transport-related GHG emissions by 23-36% per area compared to the BAU scenario (Magnusson et al., 2019).

Another example of MFA application in mass management is found in the study by (Rugani & Petucco, 2025), detailed later in the Subsection 7.2.1. In this study, MFA was used to quantify the flows of excavated soil in Luxembourg and, in conjunction with LCA, evaluate the environmental impacts of current soil management practices, contrasting these impacts with alternative scenarios where excavated soil is reused as a substrate for nature-based solution (NbS) projects rather than being backfilled (Rugani & Petucco, 2025). The flows of the excavated soil are presented in Figure 7-8 below.

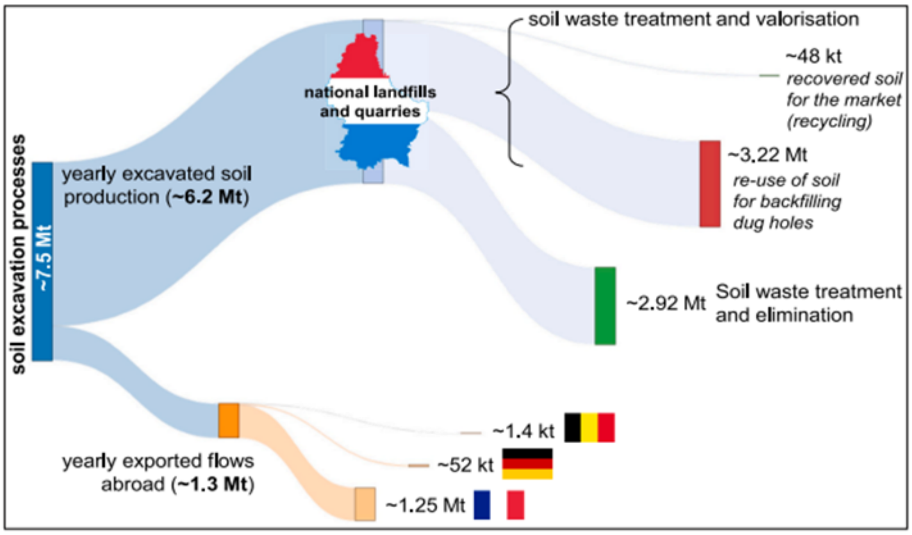


Figure 7-8. The excavated soil flows from the extraction in Luxembourg (construction sites) to different destinations within the country and abroad. Figures reflect the average flows among the yearly data recorded from 2016 to 2019, from (Rugani & Petucco, 2025).

On average, around 7.5 Mt of excavated soil is produced each year. Of this, about 43% is typically recovered to backfill holes in existing quarries, while the rest is either treated and discarded on-site as material that cannot be further valued (~39%) or exported abroad (~17%) (Rugani & Petucco, 2025). As noted by (Brunner & Rechberger, 2005) MFA is typically used as an input for further LCA, which is also the case here.

A similar study conducted in Shenzhen, China, detailed later in the Subsection 7.1.2 assessed the sustainability of ESR management using a dynamic approach that integrates MFCA with life cycle thinking, finding that transitioning to effective recycling and improving material flow management could significantly reduce environmental impacts and costs, offering long-term benefits for both the economy and the environment (Wang et al., 2024).

A national-scale MFA was carried out to assess the flows of mined and natural aggregates (sand, gravel, and crushed rock), construction excavation materials (CEMs) - which may include rock, gravel, sand, clay, soil, or mixed geological materials depending on local conditions, as well as aggregates embedded in manufactured materials and those recovered from CDW in Norway for 2021 (Ljunge et al., 2026). The analysis indicates that aggregate production reached 16.7 t per capita, with approximately 30% exported, while domestic consumption (12.8 t per capita) was predominantly supplied by crushed rock. Road infrastructure accounted for the largest share of material accumulation in stock. In parallel, construction activities generated considerable quantities of CEMs, with infrastructure projects contributing 77% and building projects 23% (Ljunge et al., 2026).

Additionally, MFA was used to examine the flow of construction minerals, including different types of rock such as limestone, sandstone, granite, etc., and sand and gravel, and assess their sustainability impacts in the Northwest of England (McEvoy et al., 2004). Moreover, MFA was used to track sand flows and stocks across the economy, offering a practical example that demonstrates how sand flows and stocks are estimated within global construction aggregates (Watari et al., 2025).

In relation to the reuse of ESR, especially from underground projects, (Haas et al., 2020) proposed that MFA should be a compulsory component in estimating the volumes of ESR. They also suggested the creation of a dedicated European authority to oversee material management, along with the establishment of a legal and technical database to publish reports and data on resource status. The main objective should be to achieve a reuse rate of 90% or more, with the goal of reducing landfilling. Industries should be incorporated into the European reuse authority, contributing to classification models that cover geotechnical, petrophysical, geological, mineralogical, and geochemical parameters within regulatory frameworks Figure 4-9 and Figure 7-9. This new authority would manage material usage and waste, focusing on the development of MFA and the operation of the technical database (Haas et al., 2020).

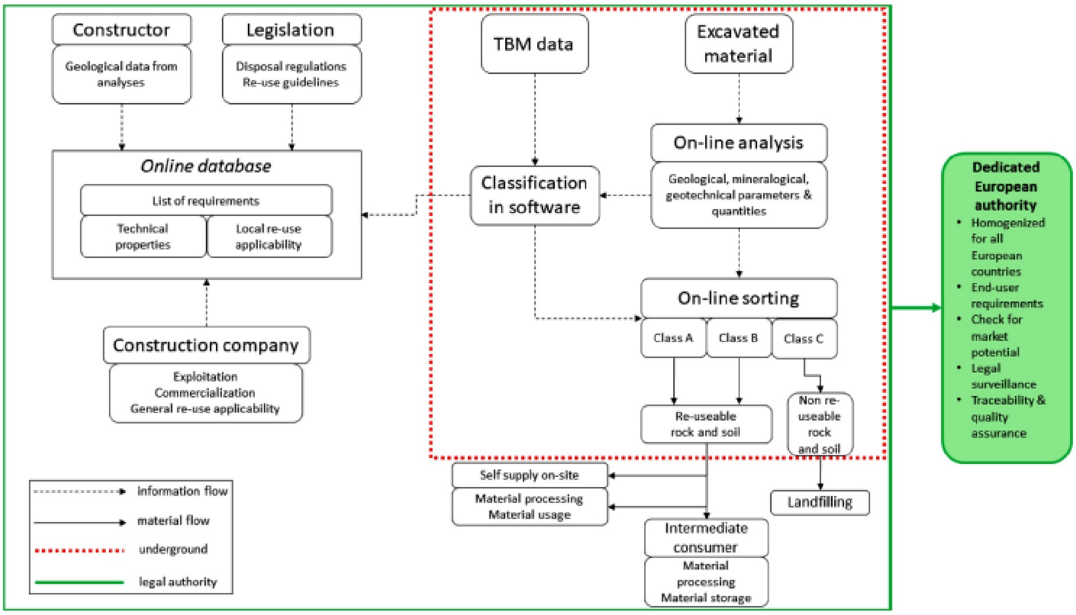


Figure 7-9. Conceptual management and caption of reuse potential for excavated rock and soil framed by a legal European authority (green line). The red square indicates tasks to be conducted on-site, respectively, underground. TBM stands for tunnel boring machine. From (Haas et al., 2020).

7.1.2 Addressing Uncertainty in Mass Management

According to the Oxford English Dictionary, uncertainty is defined as “the quality of being uncertain in respect of duration, continuance, occurrence, etc.; liability to chance or accident, as well as the quality of being indeterminate as to magnitude or value; the amount of variation in a numerical result that is consistent with observation” (Oxford English Dictionary, 2024a) or “the state of not being definitely known or clear; doubtfulness or vagueness”, among other definitions (Oxford English Dictionary, 2024b). Uncertainty can be divided into two primary types: epistemic, which reflects incomplete knowledge, and linguistic, which arises from the imprecision of language. Epistemic uncertainty includes measurement error, systematic error, natural variation, model uncertainty, and subjective judgment. Linguistic uncertainty, on the other hand, can be further classified into five distinct types: vagueness, context dependence, ambiguity, indeterminacy, and underdetermination (Burgman, 2005).

When dealing with uncertainties, Monte Carlo analysis provides a method to address numerical problems. When a parameter in a model is uncertain, it is necessary to construct a model that accounts for that uncertainty by selecting a statistical distribution and defining its parameters, with Monte Carlo using various distributions such as uniform, triangular, normal, lognormal, beta, binomial, exponential, and Poisson to represent different types of uncertainty. By repeatedly introducing random variations, the method generates estimates of the likelihood of different outcomes (Burgman, 2005). For a more detailed explanation of Monte Carlo analysis, please refer to (Burgman, 2005).

An example of addressing uncertainties in ESR management is provided by (Wang et al., 2024), where the combined use of MFCA and LCA was applied to assess ESR flows and evaluate the sustainability of the ESR management system in Shenzhen, China, by quantifying annual mass balances, evaluating the environmental and economic impacts of various disposal methods, and identifying key contributing factors. The system boundary of ESR management in Shenzhen is shown in Figure 7-10 below.

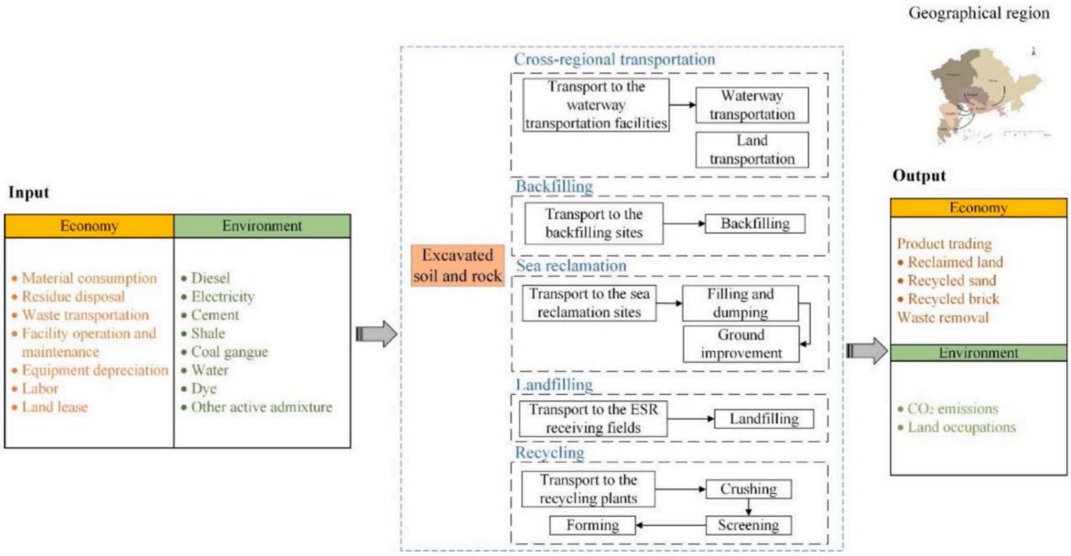


Figure 7-10. System boundary of the ESR management in Shenzhen, from (Wang et al., 2024). Note: In the context of ESR management in Shenzhen, cross-regional transportation was regarded as a disposal method without considering any subsequent processing and utilization in those cities.

To identify uncertainties related to ESR flows in Shenzhen, the study employed the method developed by (Laner et al., 2016), who assessed the uncertainty of MFA input data on plastics flows in major Austrian consumption sectors in 2010. Their approach focused on evaluating data quality as the foundation for estimating the uncertainty of input data (Laner et al., 2016), shown in Table 7-3. (Wang et al., 2024) identified four main sources of uncertainty: 1) the data acquisition process, which relied on interviews and on-site surveys and may not accurately reflect the proportions of ESR treatment flows; 2) sampling methods for interviews and field investigations; 3) the vague categorization of CDW and treatment flows in official documents; and 4) temporal variations in ESR disposal rates. Flow values were adjusted to account for associated uncertainties, reflecting the variability of each mass flow (Wang et al., 2024). The calculation of uncertainties was based on the individual coefficients of variance (CVs), which are determined by dividing the standard deviation by the mean.

Table 7-3. Definition of data quality indicators and qualitative evaluation criteria for the application of scores 1 to 4, from (Laner et al., 2016).

Indicator	***Definition***	***Score: 1***	***Score: 2***	***Score: 3***	***Score: 4***
Reliability	Focus on the data source: documentation of data generation, e.g., assessment of sampling method, verification methods, and reviewing processes.	The methodology of data generation is well documented and consistent, with peer-reviewed data.	The methodology of data generation is described, but not fully transparent; no verification.	Methodology is not comprehensively described, but the principle of data generation is clear; no verification.	Methodology of data generation unknown; no documentation available.
Completeness	Composition of the date of all relevant mass flows. Possible over- or underestimation is assessed.	Value includes all relevant processes/flows in question.	Value includes the quantitatively main processes/flows in question.	Value includes partially important processes/flows, and the certainty of data gaps.	Only fragmented data available; important processes/mass flows are missing.
Temporal correlation	Congruence of the available date and the ideal date concerning time reference.	Value relates to the right time period.	Deviation of value 1 to 5 years.	Deviation of value 5 to 10 years.	Deviation more than 10 years.
Geographical correlation	Congruence of the available date and the ideal date concerning the geographical reference.	Value relates to the studied region.	Value relates to a similar socio-economic region (GDP, consumption pattern).	Socioeconomically, a slightly different region.	Socioeconomically very different region.
Other correlation	Congruence of the available date and the ideal date with respect to technology, products, etc.	Value relates to the same product, the same technology, etc.	Values relate to similar technology, product, etc.	Values deviate from the technology/product of interest, but rough correlations can be established based on experience or data.	Values deviate strongly from the technology/ product of interest, with correlations being vague and speculative.

For each indicator, as presented in Table 7-3 (reliability (CV_r), completeness (CV_c), geographical correlation (CV_g), temporal correlation (CV_t), and other correlation (CV_o), CVs were calculated to determine the overall CV (Wang et al., 2024). The calculations were as follows:

$$CV = a \times e^{b \times (score-1)} \tag{1}$$

$$CV_r = a \times e^{b \times score} \tag{2}$$

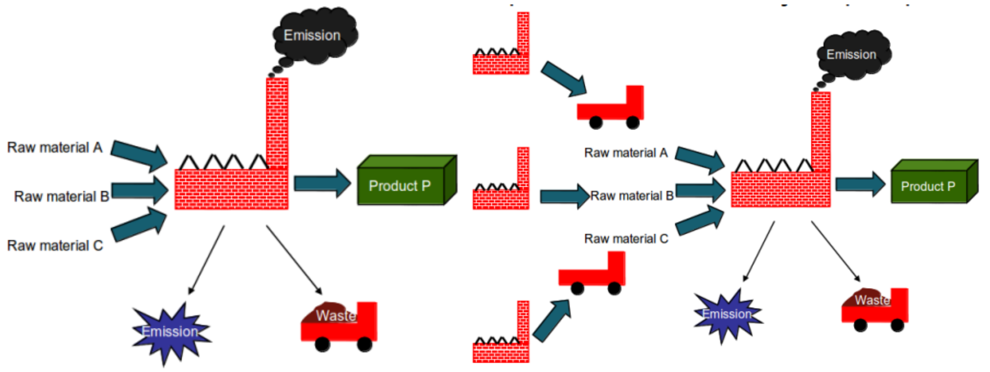
$$CV_{total} = \sqrt{CV_r^2 + CV_c^2 + CV_g^2 + CV_t^2 + CV_o^2} \tag{3}$$

The scores, ranging from 1 to 4, are presented in Table 7-3. For different sensitivity levels, the parameters a are 0.375 (not sensitive), 0.75 (medium sensitive), and 1.5 (highly sensitive). b is 1.105 (Wang et al., 2024). For the uncertainty estimate calculation results for the ESR treatment activity, please refer to (Wang et al., 2024).

In addition, the uncertainties for the environmental and economic assessment of ESR management were determined through Monte Carlo simulations. The authors conducted 20,000 iterations with a 95% confidence level using Oracle's Crystal Ball, a widely used tool integrated into Microsoft Excel, to analyze the uncertainties and variations in inventory data (Sonnemann et al., 2003). Normal distributions were applied to energy consumption, GHG emission factors, and economic input data, while a triangular distribution was used for land occupation due to variations in geological conditions at different ESR treatment facilities (Wang et al., 2024).

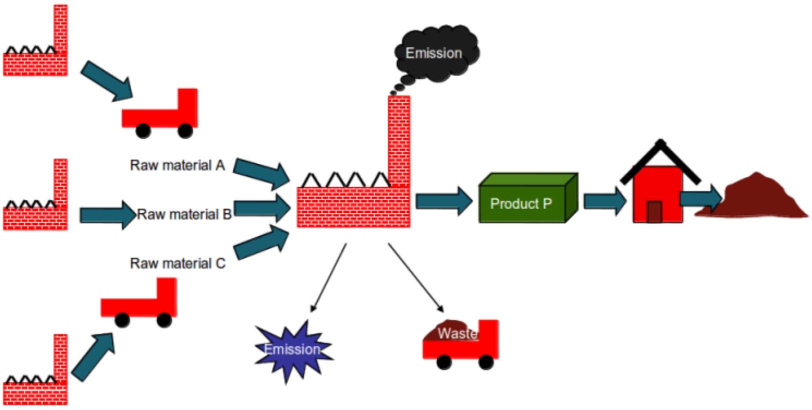
7.2 Life cycle assessment

LCA is a technique for assessing the environmental impact of products and services by analyzing the entire industrial system that contributes to their creation, usage, and disposal. It traces a product's journey from the "cradle," where raw materials are extracted from natural resources, through the stages of production and use, and ultimately to its "grave," or final disposal, as can be seen in Figure 7-11c. This thorough process provides a complete picture of the environmental consequences associated with each stage of a product's lifecycle (Baumann & Tillman, 2004). Additionally, other life cycle perspectives such as *gate-to-gate* (Figure 7-11a) and *cradle-to-gate* can be considered as well (Figure 7-11b).



a) gate-to-gate

b) cradle-to-gate



c) cradle-to-grave

Figure 7-11. Product life cycles in an LCA model, from (Division of Environmental Systems Analysis & Department of Technology Management & Economics, 2024).

The tool was developed during the 1980s and 1990s in Europe and the U.S. (Brunner & Rechberger, 2005), with its roots tracing back to an initial study by the Midwest Research Institute (MRI) in 1969. This study analyzed the resource consumption, emissions, and waste flows of different beverage containers for the Coca-Cola Company (Guinée et al., 2011). It was later followed by a comparable study for the U.S. Environmental Protection Agency in 1974 (Hunt, 1974), and another conducted by (Basler and Hofman Ingenieure und Planer, 1974) in Switzerland (Guinée et al., 2011). During the 1990s and 2000s, the Society of Environmental Toxicology and Chemistry (SETAC) was instrumental in bringing together LCA practitioners, users, and scientists to enhance and align LCA frameworks, terminology, and methodologies. A significant result of this effort was the SETAC "Code of Practice". Since 1994, the International Organization for Standardization (ISO) has also contributed to LCA, with SETAC concentrating on the development and harmonization of methods, while ISO took on the task of formalizing and standardizing these methods and procedures (Guinée et al., 2011). Accordingly, a series of ISO LCA standards, known as the 14040 series, was developed:

ISO 14040 (2006E): Environmental management - Lifecycle assessment - Principles and framework' and *ISO 14044 (2006E): 'Environmental management - Lifecycle assessment - Requirements and guidelines'* (Baumann & Tillman, 2004; Brunner & Rechberger, 2005; Guinée et al., 2011; ISO, 2006).

The overall methodological framework for LCA is illustrated in Figure 7-12 below.

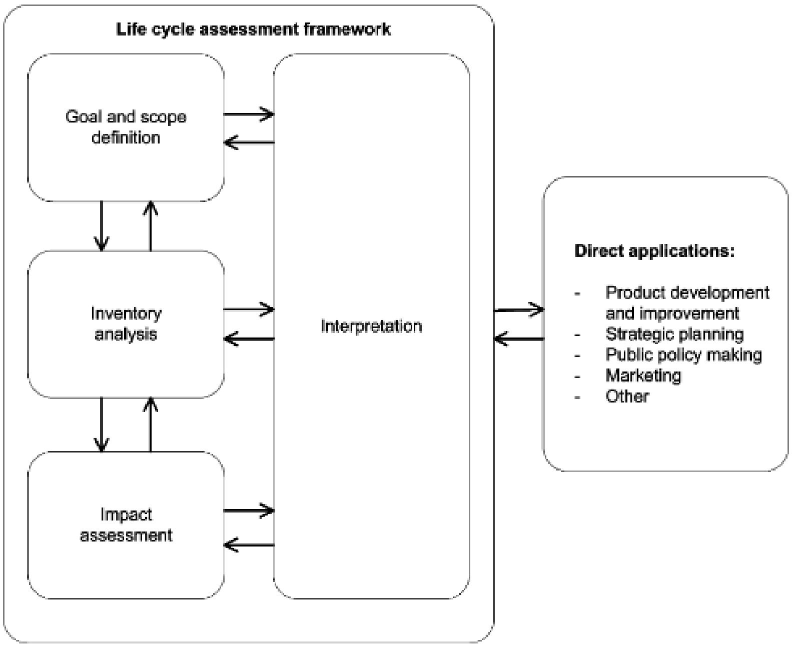


Figure 7-12. The general methodological framework for LCA, from (ISO, 2006).

"Goal and scope definition" includes defining the study's objective, outlining the scope in terms of time, location, and technology, and determining the required level of detail based on the study's goals. It also involves describing the product(s) being analyzed and establishing the functional unit (Brunner & Rechberger, 2005).

The *"inventory analysis"* involves creating a system model that aligns with the defined goals and scopes, basically representing a flow model of the technical system within established system boundaries (Baumann & Tillman, 2004). In more detail, it consists of compiling a table that details the inputs and outputs, or "environmental interventions," linked to the functional unit. This process involves establishing system boundaries, choosing relevant processes, collecting data, and conducting allocation for multifunctional processes (e.g., a power plant supplying energy for multiple products) (Brunner & Rechberger, 2005).

The *"impact assessment"* phase involves analyzing and interpreting the inventory data in relation to environmental impacts and societal concerns (Brunner & Rechberger, 2005), essentially converting the inventory results into more environmentally meaningful information (Baumann & Tillman, 2004). This includes selecting relevant impact categories, such as resource depletion, climate change, human and ecotoxicity, and noise, among others (Brunner & Rechberger, 2005). In the "classification" step, inventory data is categorized according to the specific environmental impact they contribute to (Baumann & Tillman, 2004). During the "characterization" step, the environmental interventions are quantified using a common unit for each category (e.g., kg CO2 equivalents for climate change), which allows for the aggregation of a single score for each category, referred to as the category indicator result, as illustrated in Figure 7-13. Optional steps like "normalization" and "weighting" of impact categories can then be applied, leading to an overall final score (Brunner & Rechberger, 2005).

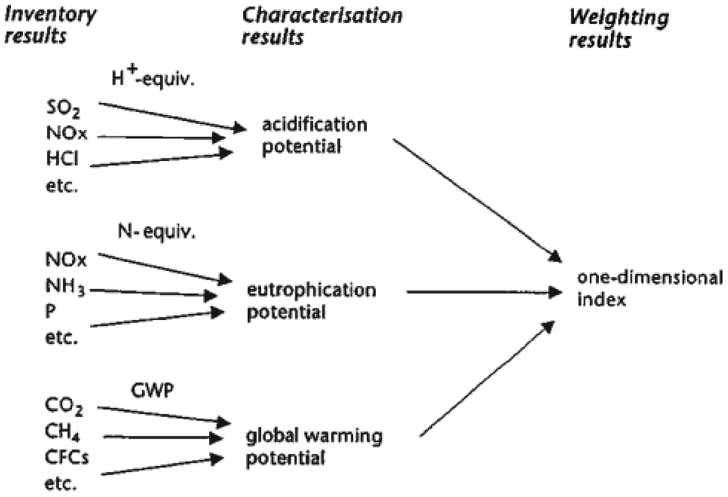


Figure 7-13. Illustration of the stepwise aggregation of information in LCA, from (Baumann & Tillman, 2004).

The *"interpretation"* of the results entails assessing their reliability, robustness, consistency, and completeness, among other factors. This phase also involves forming conclusions and providing recommendations derived from the analysis (Brunner & Rechberger, 2005).

LCA can be applied in various areas, including decision making, market communication (e.g., environmental product declaration), product development and purchasing, national level decisions (e.g., on waste treatment strategies), and identifying opportunities for improvement, as shown in Figure 7-12 (Baumann & Tillman, 2004; Brunner & Rechberger, 2005).

Additionally, there are different types of LCA assessments, such as Life Cycle Costing (LCC), which provides a consistent framework for integrating LCA with economic evaluations, encompassing three types of LCC assessments (Hunkeler et al., 2008): *Conventional, Environmental, and Societal*. *Conventional LCC* focuses on traditional financial costs from the perspective of the company. *Environmental LCC* builds upon this by incorporating costs borne by all stakeholders and aligning with LCA boundaries. *Societal LCC* goes a step further by including externalities, such as environmental and social impacts, and assigning monetary values to these effects. Together, these types of LCC provide a holistic approach to economic evaluation, either in conjunction with LCAs or as independent metrics (Martinez-Sanchez et al., 2015).

Furthermore, in 2006, the European Commission initiated the CALCAS (Co-ordination Action for Innovation in Life Cycle Analysis for Sustainability) project to streamline and enhance LCA methodologies. This effort resulted in the development of the Life Cycle Sustainability Analysis (LCSA) framework, which extends the scope of LCA to include environmental, social, and economic sustainability aspects. The LCSA framework identifies existing knowledge gaps, suggests research to address them, and shifts the focus from product-level issues to broader sector and economy-wide concerns (Guinée et al., 2011). The framework is shown in Figure 7-14 below.

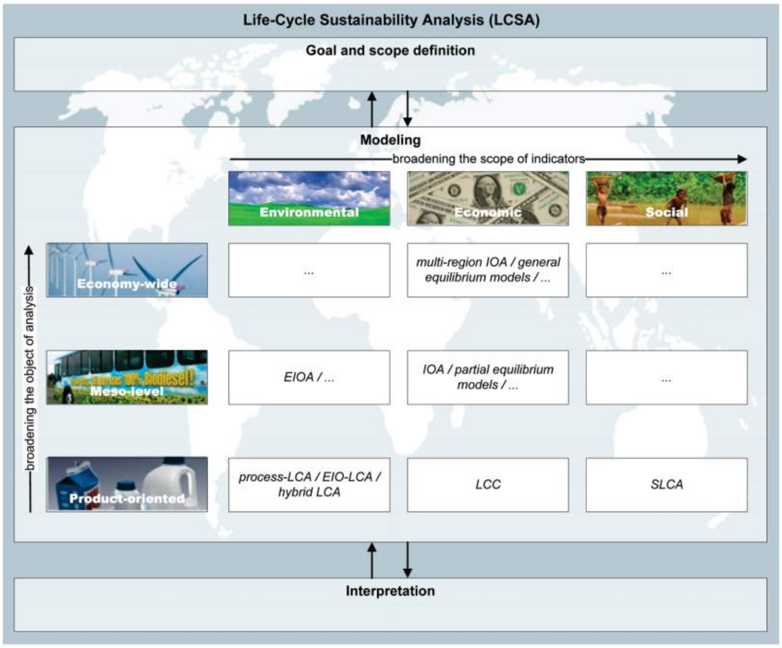


Figure 7-14. Transdisciplinary integration framework for life cycle sustainability analysis, from (Guinée et al., 2011).

7.2.1 The application of LCA in mass management

In the context of ESR management, LCA can serve as a valuable tool for quantifying the environmental impacts associated with different uses of soil and rock generated from construction activities, particularly within the broader framework of CDW (Rugani & Petucco, 2025), while also helping to evaluate the environmental and social costs associated with unsustainable soil management (Becker et al., 2020).

In the report *"Techno-economic and Environmental Assessment of Construction and Demolition Waste Management in the European Union"* (European Commission: Joint Research Centre, 2023), and in the article by (Cristóbal et al., 2024), an LCA and an LCC were used to quantify potential savings from increasing the reuse and recycling of ESR and dredging spoils (DDS). Dredging spoils are defined as the organic matter removed during dredging, which includes sand, soil, silt, clay, debris, and other organic sediments (Geoform International, n.d.). Figure 7-15 below illustrates the system boundaries for the four waste management pathways studied in this research, defined in Table 4-2, Section 4.5. The functional unit used in the study was the management of one ton of each fraction (i.e., ESR and DDS) from CDW (Cristóbal et al., 2024). Five ESR and DDS management scenarios were analyzed to assess their potential contribution to the EU's CE objectives and the European Green Deal (see Table 7-4 below). For further details on the methodology and study, please refer to (Cristóbal et al., 2024).

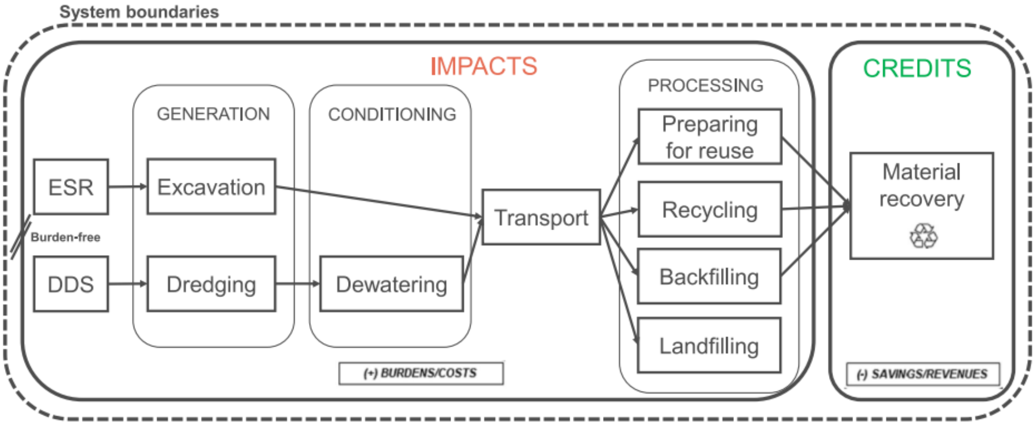


Figure 7-15. System boundaries for the four waste management pathways. Impacts include burdens (LCA) and costs (LCC) coming from the waste management of each fraction; whereas, credits include savings (LCA) and revenues (LCC) from material recovery, from (Cristóbal et al., 2024).

Table 7-4. Analyzed scenarios in the study ((Cristóbal et al., 2024).

Scenario	**Description**
Baseline (BSL)	Represents the status quo
Maximum Recycling Potential (MRP)	Based on stakeholder consultations and data from the literature, focusing on technical feasibility
Maximum Preparing for Reuse Potential (MPP)	Based on stakeholder consultations and data from the literature, focusing on technical feasibility
Target on Recycling Potential (TRP)	Legislative target for recycling, aiming for at least 70% recycling of CDW fractions in line with WFD, prioritizing recycling over backfilling
Target on Preparing for Reuse Potential (TPP)	Legislative target for preparing materials for reuse, in line with EU taxonomy requirements, at least 90% of non-hazardous CDW must be prepared for reuse or recycling on construction sites, excluding backfilling

The main findings of the study suggest that promoting the preparation for reuse and recycling of ESR and DDS, following the waste hierarchy, could lead to significant contributions to annual GHG reductions and potential economic savings, estimated at up to 3.6 Mt CO2 eq. per year and EUR 12.3 billion per year (Cristóbal et al., 2024). The Table 7-5 below illustrates the contribution of each scenario to these savings.

Table 7-5. Total annual GHG emission reduction and total annual cost for the four scenarios analyzed by waste fraction - Maximum Recycling Potential (MRP), Maximum Preparing for reuse Potential (MPP), Target on Recycling Potential (TRP), Target on Preparing for reuse Potential (TPP), after (Cristóbal et al., 2024).

Scenario	**MRP**		**MPP**		**TRP**		**TPP**	
Fraction	Total GHG reduction (Mt.Co$_2$ eq.year^{-1})	Total Cost saving (billion EUR year^{-1})	Total GHG reduction (Mt.Co$_2$ eq.year^{-1})	Total Cost saving (billion EUR year^{-1})	Total GHG reduction (Mt.Co$_2$ eq.year^{-1}	Total Cost saving (billion EUR year^{-1})	Total GHG reduction (Mt.Co$_2$ eq.year^{-1}	Total Cost saving (billion EUR year^{-1})
ESR	0.3	5.4	1.2	7.6	0.2	3.3	0.2	3.3
DDS	0.4	3.8	2.4	4.7	0.4	3.5	0.7	3.5

Furthermore, according to the data, Luxembourg has consistently had one of the highest per capita waste production rates from excavated materials since the early 2000s (European Commission: Directorate-General for Environment: Flexman et al., 2024). On one hand, managing excavated soil generates significant revenue for waste treatment businesses in Luxembourg and its neighboring countries, but on the other hand, the lack of local storage capacity creates environmental and social challenges, with nearly 20% of soil waste being exported annually (Rugani & Petucco, 2025). Additionally, Luxembourg faces a shortage of facilities for treating CDW, which contributes to the continued practice of backfilling (Monier et al., 2017). To respond to the pressing need for improved soil management, the study by (Rugani & Petucco, 2025) developed a transferable framework for modeling soil reuse strategies to improve soil management in urban areas. The study employed MFA (see Figure 7-8) and an LCA with a spatial routing model to optimize transport routes and evaluate the environmental impacts of two soil management scenarios. The BAU scenario reflected current logistics with long transport routes to distant landfills, while the alternative soil recovery scenario for nature-based solution interventions (ALT) optimized transport distances by using land suitability scores for NbS implementation sites, see Figure 7-16. Adopting alternative recovery and reuse strategies could significantly reduce the carbon footprint, lowering potential warming impacts by 41% to 92% when soil is transported shorter distances (5–50 km), as approximately 35% to 50% of the environmental impacts come from transporting soil waste (Rugani & Petucco, 2025).

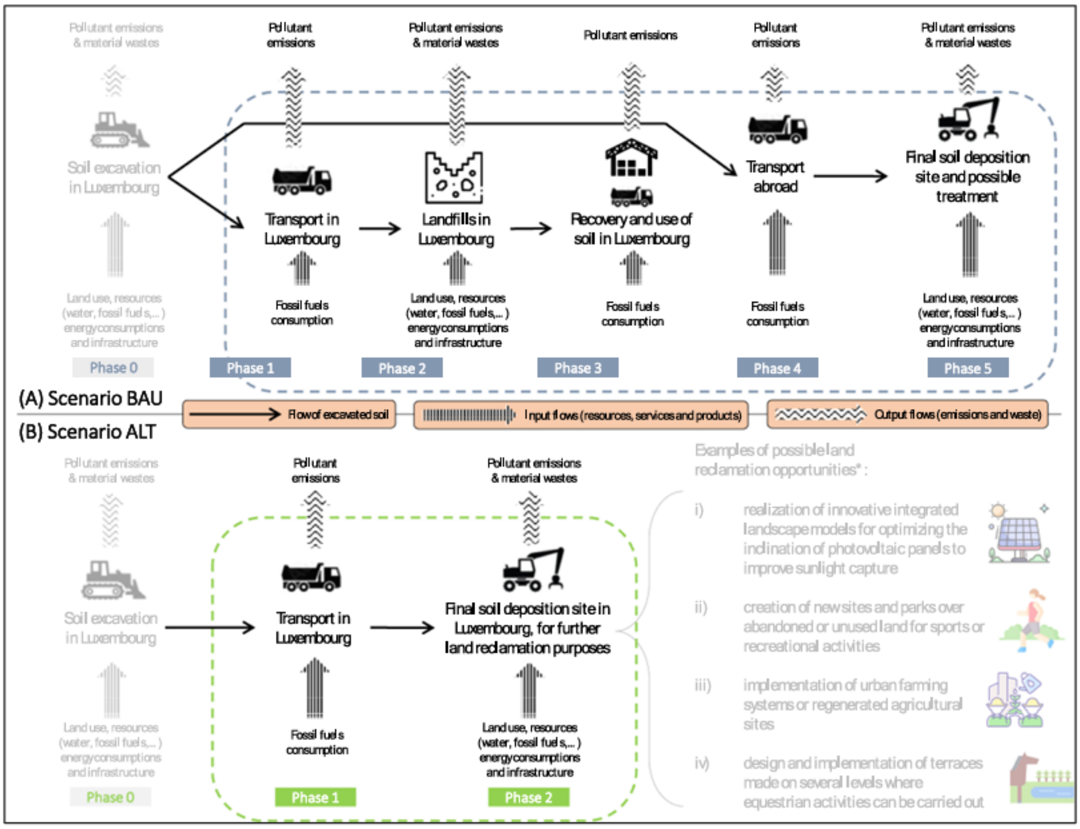


*Figure 7-16. (A) System boundary for the business-as-usual (BAU) management of excavated soils in Luxembourg; and (B) system boundary of an alternative soil recovery scenario for nature-based solution interventions (ALT model); *list of land reclamation opportunities proposed by local stakeholders, from (Rugani & Petucco, 2025).*

Another example of LCA application in excavated soil management is the study by (Zhang, Zhang, et al., 2020), which assesses the global warming potential (GWP, expressed in CO2 equivalent) of different excavated soil recycling, that is, the manufacture of ESR-based construction materials, see Figure 4-10 and Figure 4-12, and landfilling scenarios using an LCA model as shown in Figure 7-17. The study findings demonstrate that recycling excavated ESR can significantly cut GHG emissions. When compared to conventional construction materials, the scenarios indicated that using ESR produced between 2010 and 2018 to manufacture baking-free bricks and recycled baked bricks could have reduced CO_2 equivalent emissions by 1.1 to 1.5 million tons (Mt) (Zhang, Zhang, et al., 2020).

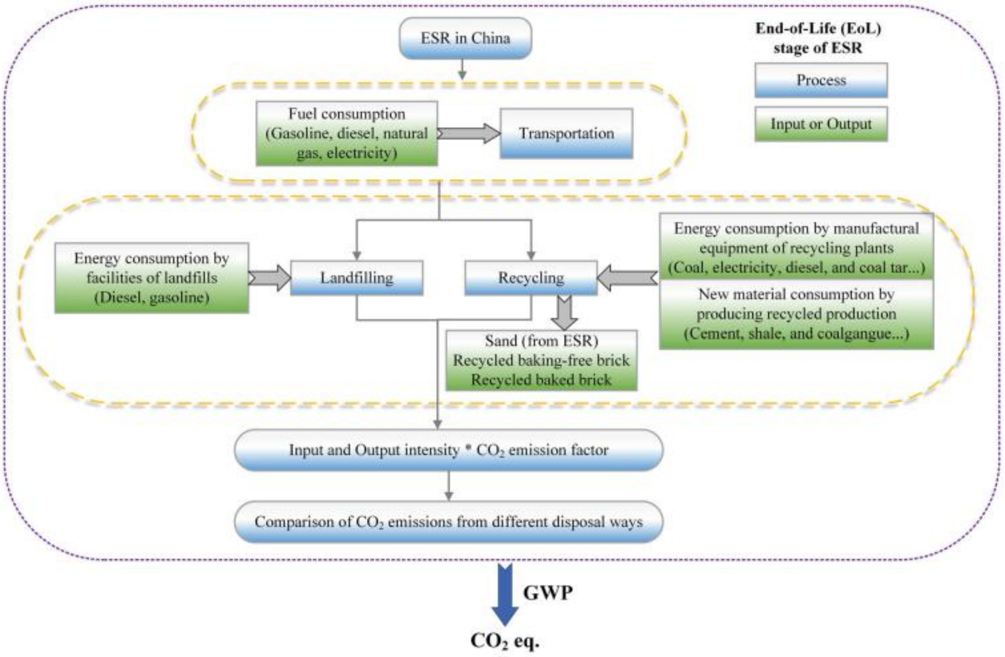


Figure 7-17. The system boundary and study scope for LCA. ESR = excavated soil and rock; GWP = global warming potential; LCA = life cycle assessment, from (Zhang, Zhang, et al., 2020).

Additionally, the previously mentioned study by (Xu et al., 2022) compares the environmental impact of using recycled crushed aggregates from excavated soil in cement-treated base materials (CTBM) with the traditional CTBM made from natural stone aggregates, as shown in Figure 4-10. Reusing excavated soil in this context can lead to an average reduction of over 26% in environmental impact (Xu et al., 2022).

7.3 Cost-benefit analysis

The core principle of CBA can be summarized as a project being deemed favorable if its benefits (“to anyone who may benefit") exceed the associated costs (Johansson & Kriström, 2018). However, the foundations of the analysis can be attributed to the nineteenth-century engineer and economist Jules Dupuit, who introduced the concept of "utility remaining to consumers," now known as consumer surplus (Dupuit, 1849), focusing on assessing the benefits and costs associated with the construction of a bridge (Johansson, 1993). The first application of CBA occurred in 1936, when the US Congress passed a flood control act that established a framework for prioritizing projects (Johansson & Kriström, 2018). In 1950, CBA was initially involved in the use of public projects, primarily in Europe, and later expanded to developing countries (Johansson & Kriström, 2018). Significant contributions to the development of the CBA’s foundations include works by (Boadway, 1975), (Drèze & Stern, 1987), (Just et al., 2005) and (Lesourne & Silvey, 1975). In general, CBA is based on welfare economics, the theory of public goods, and microeconomic investment analysis (Schönbäck et al., 1997). It can be carried out at different scales, including the county, state, national, union (e.g., EU), or global level (Johansson & Kriström, 2018).

In line with the principle of CBA outlined above, (Hanley et al., 2009) define CBA as “a technique for measuring whether the benefits of a particular action are larger than the costs, judged from the viewpoint of society as a whole”. The initial step, see Figure 7-18 is to clearly define the subject of analysis, determine whose welfare is being considered, and specify the time frame involved. Moreover, it is essential to identify the physical effects relevant to CBA, which can be quantified in terms of resource quantity or quality, price, and their influence on the well-being of the affected population, manifesting in labor hours, energy usage, pollution levels, land use, and more (Hanley et al., 2009). Environmental impact analysis is typically conducted to generate predictions regarding environmental effects (Hanley et al., 2001). Furthermore, CBA involves assigning monetary value to all relevant effects during the valuation process (Figure 7-18), which are then aggregated. This applies when market prices are available, as they provide information about the value of a product to consumers and the cost of supplying it to producers (Hanley et al., 2009).

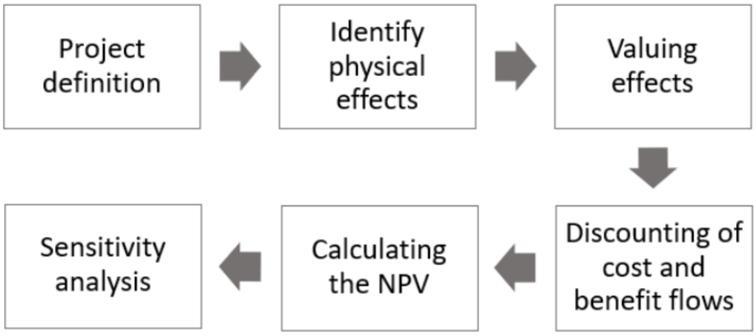


Figure 7-18. Basic steps of a CBA, from (Ohlin Saletti, 2021), (adapted from (Hanley et al., 2009)).

However, when markets are absent, meaning prices cannot be observed - such as with “goods” like biodiversity or water quality, alternative methods must be employed. These include the willingness to pay (WTP) and/or willingness to accept (WTA) approaches, as well as the Hedonic Pricing Method (HPM) (Johansson & Kriström, 2018).

WTP is a contingent valuation (CV) technique, which falls under the stated preference (SP) methods used to assess non-market goods (Johansson & Kriström, 2018; Kwak & Yoo, 2015). This approach typically involves administering a well-structured survey or questionnaire, where randomly chosen participants are asked about their WTP for a specific non-market good (Johansson & Kriström, 2018; Lim et al., 2016). On the other hand, HPM is a revealed preference (RP) technique that estimates the value of non-tradable goods by analyzing the market for related tradable goods (Marella & Raga, 2014). HPM is mainly used to assign a monetary value to environmental quality or amenities that affect residential property prices (Ecosystem Evaluation, n.d.). Both WTP and HPM are valuable in the Benefit Transfer Method, which is described as "the use of pre-existing empirical estimates from research conducted in one or more settings (study sites) to predict economic value or related information for other settings (policy sites)" (Johnston et al., 2021). For more in-depth information, readers are advised to consult (Johnston et al., 2021).

Moreover, externalities, which can be considered as unintended side effects, either positive or negative, that result from one agent's actions (consumption or production) and affect others without compensation (Johansson & Kriström, 2018), should be reflected in CBA. Negative externalities, such as pollution from car emissions or coal power stations, impose harm on others, while positive externalities, like yard maintenance or beekeeping, provide benefits to others. Positive externalities can be treated similarly to public goods by calculating the total WTP for these effects and including that value in the CBA. Conversely, negative externalities, considered public "bads," should be accounted for by adding the minimum compensation needed to accept the harm to the costs of the activity (Johansson & Kriström, 2018).

Additionally, time-based metrics, such as quality-adjusted life years (QALYs) and disability-adjusted life years (DALYs), are useful for quantifying human health impacts. QALYs assess health outcomes by considering both the length and quality of life, with one QALY representing one year of life in perfect health, adjusted for any reduction in health quality (Sassi, 2006). DALYs, on the other hand, measure health risks by integrating the dose-response relationship with the impact of diseases or disabilities on the human body (Xu et al., 2023).

Furthermore, the Net Present Value (NPV) is calculated as follows:

$$\text{NPV} = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r_1)^t} \tag{4}$$

where T is the project time, B is the benefits for year t, C is the costs for year t, and r is the discount rate. The use of a discount rate makes benefits and costs occurring at different time periods comparable (Johansson & Kriström, 2018). When the discount rate is zero, future costs and benefits are valued equally to those today. A positive discount rate, on the other hand, lowers the value of future costs and benefits in comparison to current values. Moreover, a variable discount rate, such as one that decreases over time, can be applied to promote fairness between generations (Johansson & Kriström, 2018). Finally, the last step includes conducting a sensitivity analysis to evaluate the significance of uncertainties, as analysts are required to make predictions about future physical flows and relative values (Hanley et al., 2001). When environmental impacts are factored in, this uncertainty is often more significant. The process includes recalculating the NPV by adjusting the values of key parameters, such as the discount rate, physical quantities, and qualities of input, project lifespan, and others. The objective is to identify which parameters have the greatest impact on the NPV outcome. After pinpointing the most sensitive parameters, forecasting efforts can be concentrated on refining these variables for more accurate predictions (Hanley et al., 2001). Where feasible, further actions can be taken to monitor and manage these parameters during the project's execution, although many will remain outside the control of decision-makers. The NPV decision often heavily depends on the choice of the discount rate (Hanley et al., 2001).

It should be noted that while CBA typically overlooks distributional concerns (Adler, 2013), addressing these issues becomes crucial when societal distribution is inefficient or when unequal distributions result in additional costs (Johansson & Kriström, 2018). Methods such as the social welfare function or distributional weights can be used to tackle these concerns. Additionally, a distributional analysis can be incorporated into sensitivity analysis, where benefits and costs are assigned to various groups (Johansson & Kriström, 2018).

7.4 Multi-criteria decision analysis

MCDA is a highly flexible and powerful method for handling complex, multi-objective decision-making. It is particularly useful for evaluating options that involve both conflicting objectives and diverse criteria. By breaking down problems into smaller pieces and providing a structured method for evaluating trade-offs, MCDA improves the quality of decision-making, both in the private and public sectors (Dodgson et al., 2009). The origins of the MCDA can be traced back to decision theory by (Keeney, 1982), with the key steps summarized in Figure 7-19 below.

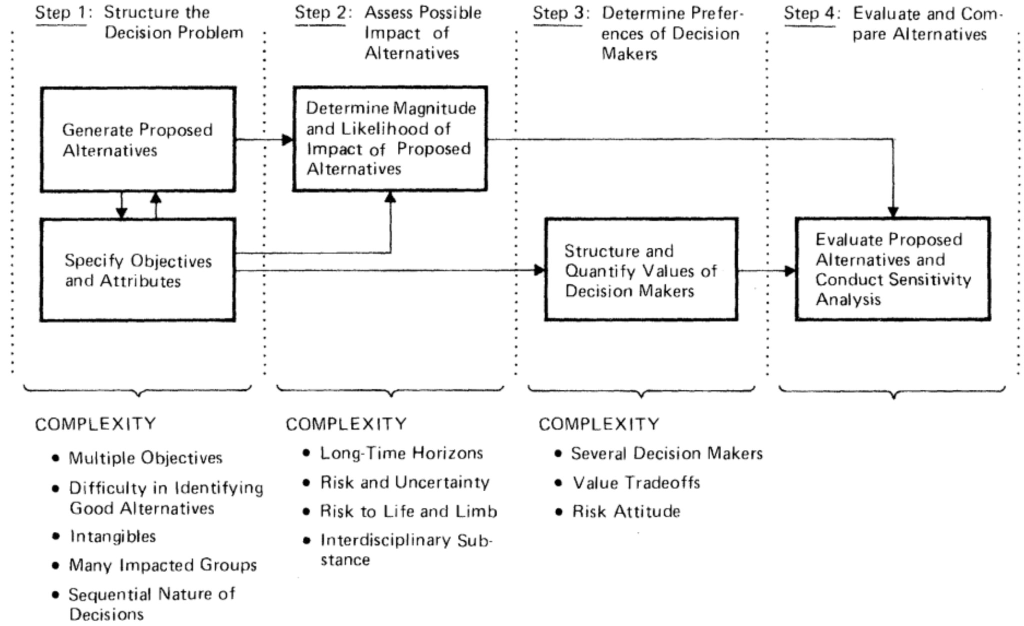


Figure 7-19. Schematic representation of the steps of decision analysis, from (Keeney, 1982).

A significant case of MCDA application involves the evaluation of potential nuclear waste disposal sites in the United States. Five sites were ranked using MCDA, but the US Department of the Environment chose the sites ranked first, third, and fifth for further investigation, rather than the top three (Merkhofer & Keeney, 1987). This led Keeney (Keeney, 1987) to conduct a follow-up analysis to identify the optimal combinations of sites, as examining two very similar sites at the same time would be inefficient. His analysis recommended a sequential characterization approach for greater cost-effectiveness, although the fifth-ranked site was still excluded from consideration (Dodgson et al., 2009).

Furthermore, the main steps in MCDA are summarized in Figure 7-20.

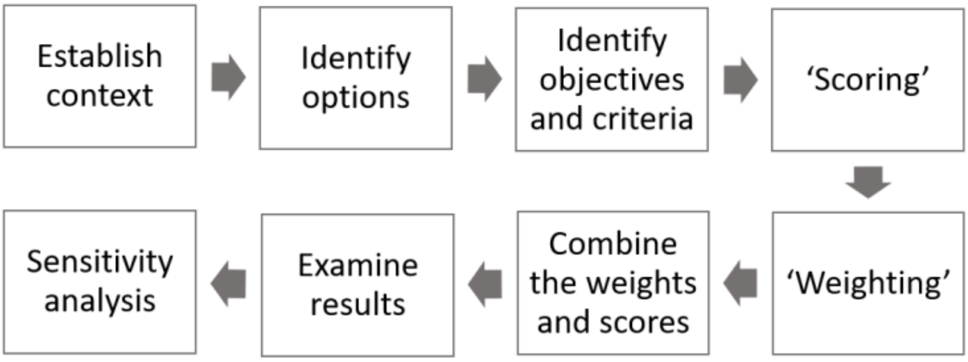


Figure 7-20. Main steps in MCDA, from (Ohlin Saletti, 2021), (adapted from (Dodgson et al., 2009)).

The first step in the MCDA process is to establish a shared understanding of the decision context, including the objectives, historical and administrative background, stakeholders, and responsible parties. It is crucial to define a high-level objective with sub-objectives, as MCDA involves balancing conflicting goals and making trade-offs. Identifying decision-makers and affected stakeholders, often through policy statements, helps define the objectives and criteria for the process (Dodgson et al., 2009).

After defining the decision context, the next step in the MCDA process is to identify the set of options to evaluate. Decision-makers typically have initial ideas or existing proposals to consider. If there are too many options, MCDA assists in narrowing them down through basic data and quick methods. Informal reviews against legal or other constraints can help filter out infeasible options. This step may be revisited later, as further stages could highlight the need for new options or ideas (Dodgson et al., 2009).

In the MCDA process, options are assessed based on their consequences, which are evaluated through specific criteria or attributes that align with the objectives. These criteria are measurable objectives derived from higher-level goals. A key distinction in MCDA is between "means" objectives (easier to measure) and "end" objectives (fundamental goals). There are two main approaches for defining criteria: "bottom-up," which examines how options differ in meaningful ways, and "top-down," which looks at overarching goals (Dodgson et al., 2009).

A key challenge in the MCDA process is combining different types of evaluations, such as monetary values and ratings, into a unified assessment. This is achieved by creating preference scales, assigning weights based on their relative importance, and calculating weighted averages. The most preferred option receives a score of 100, and the least preferred receives a score of 0, with the differences in scores reflecting the strength of preference. Relative scaling is effective when comparing multiple options simultaneously, while fixed scales are better suited for evaluating options individually, establishing a minimum and maximum threshold. Ensuring consistency in preferences is essential for obtaining reliable results. Any inconsistencies identified in the initial evaluation are addressed through several iterations to achieve consistent preferences by the end of the process (Dodgson et al., 2009).

In the weighting step, the "swing weighting" method is used to compare the preference ranges for each criterion, considering both the difference between the most and least preferred options and the context of their significance. Swing weighting is carried out in four steps, typically facilitated by a nominal-group technique. The criterion with the largest preference swing is assigned a weight of 100, and other criteria are compared against this standard. Initially, weights are assigned individually and then discussed in a group setting, with the final decisions made by key decision-makers or stakeholders. The weight-setting process is shaped by the person whose preferences are prioritized, often influenced by political and contextual factors. While MCDA seeks to represent the informed preferences of all stakeholders, achieving consensus is not always possible. In such cases, multiple weight sets can be considered to identify potential compromises. Properly managing weights is essential for the success of MCDA, ensuring that the results are meaningful and actionable (Dodgson et al., 2009).

The theory of MCDA relies on the assumption that all criteria must be mutually preference independent for the simple weighted averaging calculation to be valid. This means that the preference scores for one criterion should not be affected by the scores of other criteria, even if they are correlated in the real world (Dodgson et al., 2009). The overall weighted score is usually calculated by applying the linear additive method, which is a fundamental approach in Multi-Attribute Utility Theory (MAUT) (Keeney & Raiffa, 1993). In this method, each option's score is multiplied by the corresponding weight for each criterion. The overall weighted score (Si) for each option is calculated as:

$$S_i = \sum_{j=1}^{n} w_j s_{ij} = w_1 \, s_{i1} + w_2 \, s_{i2} + \ldots + w_n s_{in} \qquad (1)$$

where s_{ij} is the preference score for option *i* on criterion *j* and w_j *is* the weight for each criterion.

The overall ranking of options in MCDA is based on the weighted average of their preference scores, which shows how one option compares to another in terms of preference. For instance, if the total scores for options A, B, and C are 20, 60, and 80, respectively, the preference gap between A and B is twice as large as that between B and C (Dodgson et al., 2009). To better visualize the results, a two-dimensional graph can be used to display trade-offs, such as a cost-benefit comparison. This highlights the most cost-effective options, which "dominate" those that offer fewer benefits at a higher cost. MCDA often uncovers surprising results that require careful reflection. A temporary decision-making process, including working meetings, can help evaluate the validity of the results, understand their implications, and develop recommendations for the next steps. If the analysis contradicts people's intuitions, it's essential not to disregard it but to thoroughly assess the findings to ensure decisions are made with a full understanding of their potential consequences (Dodgson et al., 2009).

The final step involves sensitivity analysis, which evaluates how uncertainties in inputs or differing stakeholder opinions can influence the outcomes. This is particularly crucial for public-interest projects where disagreements may arise. The process includes consulting with interest groups to ensure that the MCDA model captures all relevant criteria. While there is often disagreement over weights, sensitivity analysis can reveal that a few options consistently perform well, with only minor variations in overall benefits (Dodgson et al., 2009).

However, it is essential to recognize that MCDA is a tool to aid, not replace, human judgment. While it helps manage complexity and competing objectives, the final decision ultimately rests with the decision-maker, who must apply their own judgment and insights to the analysis (Dodgson et al., 2009). By combining the results of sensitivity analysis with expert judgment, decision-makers can navigate uncertainties and make more informed, balanced choices, ensuring that the final decision aligns with both analytical findings and stakeholder priorities (Dodgson et al., 2009).

7.5 Key performance indicators

Key performance indicators (KPIs) are a form of performance measurement (Fitz-Gibbon, 1990), used to evaluate the success of an organization or a specific activity, such as projects, programs, products, or other initiatives (Weilkiens et al., 2016). KPIs help guide strategic and operational improvements, provide a foundation for decision-making, and direct attention to the most important areas (KPI.org, n.d.). Managing KPIs involves setting targets (the desired performance level) and tracking progress to meet those goals, with a strong emphasis on improving performance (KPI.org, n.d.). In the context of MCDA, KPIs are often used as key criteria for evaluating various options. By measuring each option's performance against these KPIs, decision-makers can make more informed, objective, and transparent decisions that align with strategic objectives. Research by (Girdzijauskaitė et al., 2019) highlights the importance of KPIs as evaluative criteria in the MCDA decision-making process.

When establishing KPIs, it's important to adhere to the SMART criteria: they should have a Specific purpose for the business, be Measurable to ensure clear value, be Achievable with realistic targets, be Relevant to the organization’s success, and be Time-bound, meaning the outcomes are monitored over a defined and meaningful period (Indicators, 2019). KPIs can be categorized into i) *Quantitative* KPIs, which are objective and expressed as specific numeric values measured against a standard, typically free from distortion, personal biases, or interpretations, and ii) *Qualitative* KPIs, which reflect non-numeric adherence to a standard or involve interpretations based on personal feelings, preferences, opinions, or experiences (Wikipedia, n.d.). Additionally, the connection between KPIs and indicators can be understood as follows: KPIs set the values for comparison, whereas indicators represent the raw data that can be input into systems for aggregation (Wikipedia, n.d.).

Furthermore, various types of indicators have been developed for different purposes. In the context of CE, several circularity metrics have been proposed across different sectors. For example, (De Pascale et al., 2021) identified 61 indicators for measuring CE at the micro, meso, and macro levels, highlighting that while these indicators are valuable for supporting circularity, there is currently no standardized framework for measuring CE. In this regard, the development of the international standard ISO 59020:2024 has played a key role in bringing structure and consistency to the measurement of circularity, helping to establish more standardized metrics for assessing CE performance.

ISO 59020:2024 CE – Measuring and assessing circularity performance offers guidelines for organizations to evaluate and measure their circularity performance within specific economic systems. It standardizes the data collection and calculation process using both mandatory and optional circularity indicators, ensuring consistent and reliable outcomes. The standard provides a systematic approach for defining system boundaries, selecting appropriate indicators, and interpreting data to assess circularity at multiple levels. This standard plays a vital role in advancing the transition to CE by helping organizations minimize resource consumption and facilitate the circulation of materials. It supports environmental sustainability and aligns with the United Nations Agenda 2030 and the SDGs (International Organization for Standardization, 2024).

7.5.1 Identified indicators in the reviewed literature

Based on the reviewed evaluation methods in the literature, Table 7-6 presents the identified indicators for the management of ESR, grouped into dimensions that reflect different evaluation perspectives.

Table 7-6. Identified Indicators for the Management of ESR

Indicator dimension	***Indicator***	***Description / Metric***
MFA *& circularity*	Total excavated volume	Total quantity of soil and rock generated (m^3 or t/year)
	Material demand	Quantity of soil and rock required within projects or region (m^3 or t/year)
	Net material balance	Difference between generated and required volumes (surplus/deficit)
	Reuse rate	Share of material directly reused on-site or cross-project (%)
	Recycling rate	Share of material processed into secondary aggregates (%)
	Backfilling rate	Share of material used for low-grade recovery (%)
	Landfilling rate	Share of material disposed of in landfills (%)
	Export rate	Share of material transported outside the region/country (%)
	Material accumulation in stock	e.g. in roads
Environmental (LCA)	GHG emissions	Climate impact from material management (t CO_2-eq/year)
	GHG intensity	Emissions per unit of material managed (kg CO_2-eq/m^3 or t)
	Transport-related emissions	Share of GHG from material transport (%)
	Energy use	Energy consumption from transport and processing (MJ/m^3 or t)
	Virgin material substitution	Share of primary aggregates replaced by reused/recycled ESR (%)
Economic (LCC / MFCA)	Total system cost	Total cost of ESR management (€/year or €/scenario)
	Cost per unit managed	Cost per m^3 or ton of ESR
	Transport cost share	Share of total cost attributed to transport (%)
	Avoided disposal costs	Savings from reduced landfilling (€/year)
	Avoided virgin material costs	Savings from replacing natural aggregates (€/year)
Spatial & logistics	Transport distance	Average and total transport distance (km)
	Material reuse distance	Distance between excavation and reuse sites (km)
	Facility coverage	Number and spatial distribution of recycling/logistics hubs

	Local reuse share	Share of materials reused within a defined radius (%)
Quality & governance	Material quality class	Geotechnical and environmental suitability categories
	Regulatory compliance	Compliance with waste/end-of-waste criteria (yes/no or %)
	Traceability	Existence of material tracking/passport systems

Overall, the reviewed studies indicate that effective management of ESR is a multidimensional challenge requiring the integration of multiple evaluation methods. From these methods, relevant indicators can be identified to support the systematic assessment of circularity and sustainability across alternative management strategies.

In addition to this, and as introduced earlier in the Section 1.1 a set of indicators and KPIs related to mass management is presented in Table 7-7 below. These KPIs are derived from the pre-study *"Mass Management – Indicators and Key Performance Indicators for Reduced Climate Impact in Procurements"* (Andersson-Sköld et al., 2022).

Table 7-7. Indicators and KPIs that emerged from the analysis, from (Andersson-Sköld et al., 2022). The original table is in Swedish, while the English translations have been provided by the author.

Indicator	**Suggested KPI**
The total amount of emerged masses	Recycling rate/proportion
Amount of recycled masses	The proportion of the total proportion that could be recycled
The amount of mass that is recycled on-site	Proportion that is recycled on-site
Amount of mass that is recycled off-site	Proportion that is recycled off-site
Amount of newly extracted material from the source	Proportion of newly extracted material from source
Quality requirements - degree of contamination	Proportion of masses that can be recycled
Quality requirements - technical usability	The proportion of masses that can be recycled after treatment
The amount of mass that can be recycled	Fulfillment of the requirements according to the AMA
Amount of materials purchased	KPI regarding poison spraying
Quantity of transport	KPI regarding the management of masses with invasive species
Quantity of transportation work	Health criteria
Assessed environmental impact	Environmental/eco-criteria
Assessed health impact	Sustainability criteria (e.g., SCORE-based)
	The overall benefit versus the unwanted effects
The amount of masses that landfills have permits to receive	The relationship between tons of mass deposited by the project and the total masses that landfills have permission to receive
Sampling costs within the project (at the place or another place)	Sampling costs for the project in relation to tons of recycled masses (on-site or elsewhere), respectively, tons of total mass
Project financial costs	Project financial costs per ton of soil mass
Socioeconomic unit costs	Socioeconomic unit costs per ton of soil masses
Something that reflects where in the value chain recycling takes place	
Project stage, or anything else that implies this, for the emergence of masses, respectively, needs	

8 Identified digital tools used within mass management

Figure 8-1 presents a summary of the identified digital tools in the literature review, with detailed descriptions of each tool provided later in the text.

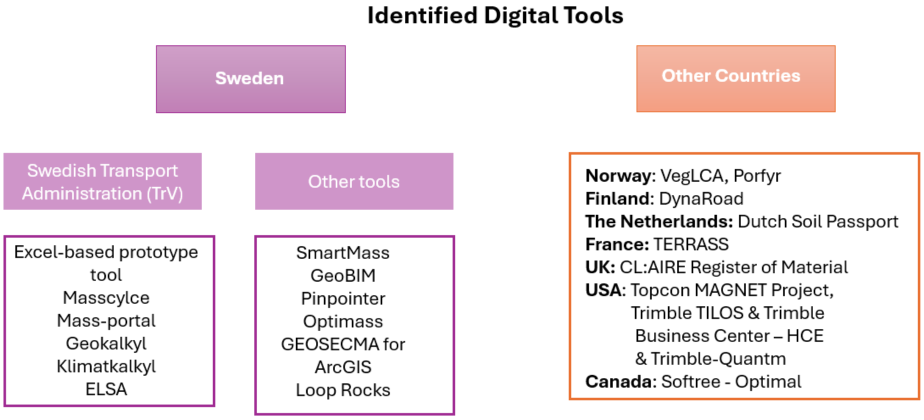


Figure 8-1. Identified digital tools within the performed literature review.

8.1 Digital tools utilized by the Swedish Transport Administration

8.1.1 Excel-based prototype tool

As mentioned in Section 1.1 an Excel-based tool was developed as part of the *"Mass Management – indicators and Key Performance Indicators for Reduced Climate Impact in Procurements"* project (Andersson-Sköld et al., 2022).

Using project data, including project cost, which encompasses the cost for mass sampling and analysis, the environmental classification of materials by contamination level, and the quantities of masses involved, the tool generates corresponding results. Additionally, it presents identified indicators and KPIs that reflect the level of project circularity. The tool structure is arranged across multiple Excel sheets, see Figure 8-2 and a detailed description below.

8.1.2 Masscycle tool

Building on the earlier study *"Mass Management – Indicators and Key Performance Indicators for Reduced Climate Impact in Procurements"*, a prototype was updated, developed, and tested on two TrV's road infrastructure projects within the master's thesis *"Masscycle - A Tool for Circular Project Planning of Sustainable Mass Management"* (Olsson & Jansson, 2024). The following Figure 8-2 and Figure 8-3 illustrates the structures of both the Excel-based prototype and Masscycle.

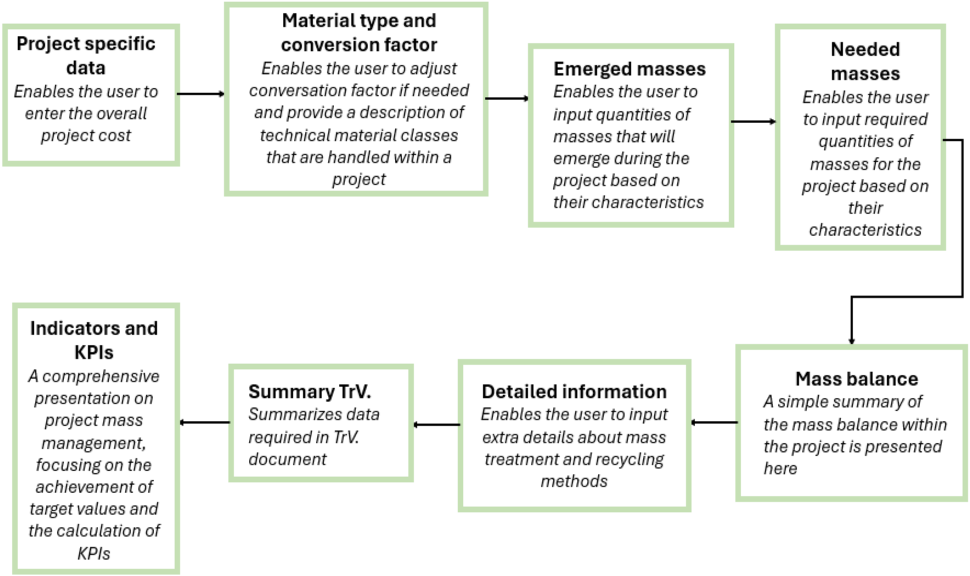


Figure 8-2. Overview of the sheets included in the Excel-based prototype, based on (Andersson-Sköld et al., 2022).

The comparison between the Excel-based prototype and Masscycle highlights several updates and improvements. The Masscycle tool enhances the Prototype by adding geographical divisions to the project-specific data sheet, removing project cost details, and integrating the material type conversion factor. The Emerged Masses sheet in Masscycle is expanded into five sheets, enabling users to specify emerging masses across different soil layers and areas. The Needed Masses sheet has been revised to include construction codes and areas with needs. The Matching sheet in Masscycle, which aligns with the Prototype's Mass Balance sheet, has been updated to integrate data from the Needed and Emerged Masses sheets, allowing for detailed material type and treatment specifications. The mass balance in Masscycle is divided into Utilized, Externally Needed, and Surplus masses, while the Compilations sheet summarizes and visualizes the results. Additionally, the KPI sheets in both tools assess project circularity using predefined metrics.

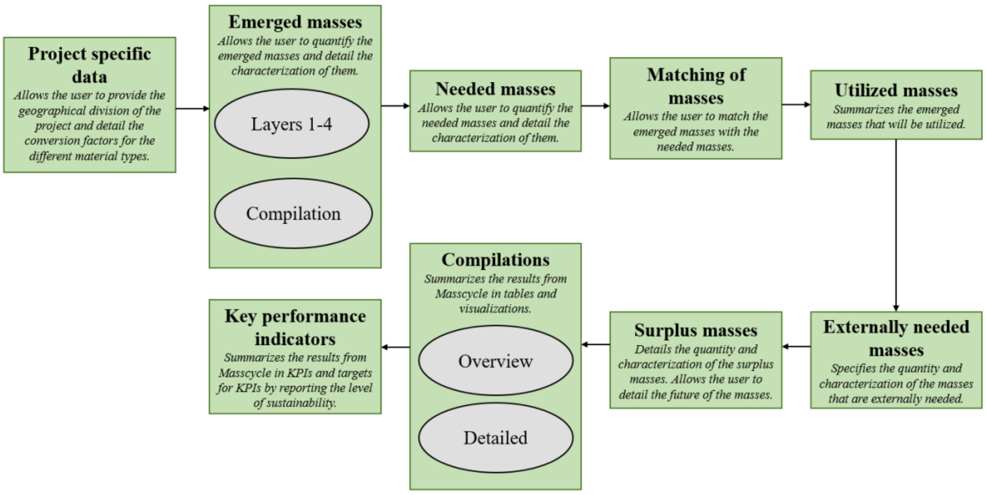


Figure 8-3. Overview of sheets included in Masscycle and their purpose, after (Jansson & Olsson, 2024).

The case studies conducted for testing Masscycle yielded valuable insights that contributed to the enhancement of Masscycle. Additionally, they furnished the project teams involved in these case studies with beneficial information regarding their projects' circularity through the use of visualizations, KPIs, and uncertainty scenarios (Jansson & Olsson, 2024). Regarding the latest update from TrV, the program has been introduced to the contractor; however, its implementation has not yet begun, according to (Jansson, 2024).

8.1.3 Mass-portal

In spring 2024, the master's thesis work *"Increasing coordination of excavated material between infrastructure projects: Creation of a digital platform for the coordination of excavated material at the Swedish Transport Administration*" (Andersson & Borre, 2024) developed the Mass-portal platform. This platform aims to coordinate TrV infrastructure projects in the western region of Sweden to reduce costs, environmental impact, and demand for new materials, promoting a circular economy. Based on the ArcGIS online web mapping software, it is designed for use during project planning stages (Andersson & Borre, 2024). To use Mass-portal effectively, input data about material parameters is required. Geokalkyl can provide valuable information on the volume, technical, and environmental properties of materials in the early stages. While Mass-portal can be utilized at early stages to assess nearby projects, uncertainties are higher due to limited data. As the project progresses from planning to construction, Mass-portal becomes increasingly useful as the information becomes more reliable (Borre, 2024).

8.1.4 Geokalkyl

AFRY (formerly ÅF) and Sweco, commissioned by TrV, have developed a tool to compare alternative alignments of large infrastructure projects such as roads or railways within designated corridors. By assessing each option and identifying the major costs associated with mass management and geotechnical reinforcement measures, designers can use the new data to adjust the project profile or alter the alignment. This adjustment aims to reduce costs, lower energy consumption, and CO_2 emissions, or achieve a better mass balance. Concerning mass balance, the tool considers excavation, filling, transportation, crushing, laying, and compacting of rock or soil within the construction site. Additionally, it calculates external transportation requirements (Lindgren & Moritz, 2018).

Geokalkyl is intended for use in the early stages of TrV's planning process, which includes activities like conducting an in-depth measure selection study for new constructions and selecting a corridor or line in a road or railway plan (Lindgren & Moritz, 2018). Some of the advantages offered by Geokalkyl are:

- Quickly interpret soil-type conditions using detailed maps.
- Obtain amounts and mass balance for soil and rock handling.
- Generate a 3D construction model and soil layer showing land requirements.
- Propose geotechnical foundation reinforcements.
- Provide facility estimates calculating cost and climate impact.
- Report results and KPIs in various formats as needed (Lindgren & Moritz, 2018).

8.1.5 Klimatkalkyl

Similar to Geokalkyl, Klimatkalkyl was initially created by WSP in collaboration with, and at the request of, TrV. Since then, it has been further refined through the efforts of both IVL and Tyréns. The current model, version 7.0, has been a web application since 2016, replacing the originally developed Excel-based tool. The primary objective in developing this tool was to enable the calculation of climate impact and energy consumption associated with the construction, operation, and maintenance of transportation infrastructure (Toller, 2020).

In assessing climate impact and energy use, the model distinguishes between two main types of actions. Firstly, the impact resulting from investment measures (Input A) is evaluated by considering construction areas/components that the measures are made of, e.g., square meter bridge, kilometer tunnel, kilometer double track, or similar. Secondly, it may be derived from more comprehensive data concerning building components or the materials and energy utilized in the project (Input B). These building components encompass materials, transportation, and various work steps. Moreover, there is a more flexible Input C that accommodates databases with varying levels of detail. Additionally, Input D enables the calculation of climate impact for base contracts related to road maintenance, considering the included maintenance measures (Toller, 2020). The tool uses a life cycle perspective, defining system boundaries based on the study's purpose. Included resources are quantified and multiplied by an emission factor representing emissions from their production processes (Toller, 2020).

The main difference between Klimatkalkyl and Geokalkyl is that Klimatkalkyl is mandatory during the early stages of TrV projects, whereas Geokalkyl is only required if specified in the project description or can be used internally within TrV. The decision to use Geokalkyl is at the discretion of the project manager. Additionally, Geokalkyl can provide input to Klimatkalkyl (Borre, 2024).

8.1.6 ELSA

The ELSA (Energiledningssystem för anläggningar) project focuses on monitoring the energy and material flows associated with the TrV's activities. Its goal is to gain better control over these flows and improve their efficiency by developing an IT tool that tracks and reduces emissions contributing to climate change. The project starts by enhancing the reliability of tracking and analyzing energy consumption, emissions of climate-impacting gases, the handling of excavated materials, and environmental product declarations for purchased goods. The method is designed to provide reliable, near-real-time data, enabling precise monitoring of carbon dioxide equivalents, similar to how financial transactions are tracked in economic management (Strid, 2024; Trafikverket, 2021).

8.2 Other identified digital tools in Sweden

8.2.1 SmartMass

SmartMass, developed by Tyréns, helps manage soil and rock masses in projects by providing tools to quantify, visualize, and compare various mass management scenarios based on cost (SEK) and climate impact (CO_2 emissions). Additionally, it allows for the evaluation of five remediation methods, comparing their costs and CO_2 emissions against excavation (Tyréns, n.d.):

- Chemical oxidation via direct injection
- Barrier installation (using PetroFix) via direct injection
- Bioventilation: cover + aeration
- Covering with asphalt or concrete
- Phytoremediation using Salix spp.

The tool relies on TrV's Klimatkalykl latest version 7.0, utilizing its background data and adhering to LCA methodology, like Klimatkalykl. The tool reports emissions and costs from four categories: Transportation, Machines & Labour, Purchased Material, and Reception Facility (for disposing of excavated masses), see Table 8-1 below (Tyréns, n.d.).

Table 8-1. SmartMass Output, from (Tyréns, n.d.).

Category	Carbon Emissions	Costs
Transportation	Vehicles	Transportation costs
Machines & labour	Machines	Labour costs
Purchased material	Supplied soil, rock masses, asphalt, geotextiles, sheet pilings	Purchase costs
Reception facility	To and from facilities	Disposal cost

8.2.2 GeoBIM

In addition to SmartMass, Tyréns developed another method, GeoBIM, to improve the management of underground information related to geotechnics, geohydrology, environmental geotechnics, rock technology, and geophysics, during planning and design processes (GeoBIM, n.d.). GeoBIM is accessible as a web service used by municipalities, developers, contractors, and consultants in the construction sector. For instance, municipalities employ GeoBIM to manage and reuse data from geotechnical and environmental investigations and complete remediation projects. In collaboration with contractors and developers, consultants engaged in construction projects utilize the tool to support planning processes and the production of specific deliverables, such as volume models for excavation planning or geotechnical models for project design (Magnusson et al., 2022). With the GeoBIM model, it is possible to quickly analyze how excavation quantities and remediation are affected by changes in drawings, e.g., the location of buildings. The collected information about the masses that support the modeling could also go with the contractor and further with the masses when these have been excavated and transported to a receiving site. It is possible to get information from previously performed geotechnical and environmental surveys to accompany the masses, so that traceability is created for the masses and gives the recipient a much better picture of the properties of the masses, and thus how they can be recycled (Magnusson et al., 2022).

8.2.3 Pinpointer

With the same objective as the Mass portal during its development, but on a national scale, the Pinpointer platform aims to facilitate sustainable mass management across Sweden. It seeks to achieve this by integrating mass demand and supply through a comprehensive digital platform (Pinpointer, n.d.). By directly matching senders with receivers, considering price, environmental requirements, and transportation distance. The company handles transactions and sales of the masses while ensuring their quality and classification. Moreover, the company has an agreement with an independent environmental consultant responsible for verifying previously taken samples and performing mass classification. Additionally, new or additional samples can be taken as an extra service. Founded in 2019, Pinpointer (the name of the company as well) operates primarily in the metropolitan regions and Värmland while extending its coverage to all of southern Sweden up to Dalarna (Pinpointer, n.d.)

8.2.4 Optimass tool

The Optimass tool, developed through several research projects, offers a unique capability to match the demand and supply of soil and rock materials beyond individual construction projects. It utilizes input data, including planned construction activities and geological information from municipalities and regions, to perform system analysis calculations and identify efficient system solutions (Magnusson et al., 2022). The goal is to create an overall mass balance for a larger area based on information available during the early stages of planning. Early planning means master planning and detailed planning in the municipal planning process, as well as infrastructure planning within the TrV's framework. A mass balance, in this context, involves calculating the amount of excavated material expected from planned construction and determining how much soil and rock material is required for the same project. The purpose of establishing a mass balance at this early stage is to help municipalities and regions identify opportunities for promoting circular mass management, making it easier for both market players and public authorities. By "circular", here it means minimizing unnecessary excavation and sourcing soil and rock material from the excavated material itself (Johansson & Lundberg, 2025).

To support circularity, municipalities can take actions such as considering building requirements and plans (e.g., number of floors, elevation requirements in certain areas) and ensuring there are designated spaces for temporarily storing and sorting excavated soil and rock material for reuse (Johansson & Lundberg, 2025).

The Optimass tool is currently in active use as a calculation support system for consulting projects with municipalities and regions. It was applied to several assignments, including projects for Huddinge, Örebro, Linköping, Norrköping, Skåne County Administrative Board, and the Stockholm Region. A development project is also underway to enhance the tool's digital capabilities, to make it accessible to clients through a website (Johansson & Lundberg, 2025).

8.2.5 GEOSECMA for ArcGIS

GEOSECMA for ArcGIS helps municipalities manage map and blueprint plans, including roads, properties, traffic, pipes, zoning, and green infrastructure (Esri Partners, n.d.). A municipality in Värmland county uses it for mass management by inputting project area information to streamline planning processes. Their objective is to enhance expertise in mass management within their region (Axelsson, 2023).

8.2.6 Loop Rocks

During its operational period of 2 years, the digital tool Loop Rocks, owned by NCC, was used by 18,000 customers, resulting in material savings of 3.5 million tons per year. The tool facilitated the connection between projects to share surplus or receive material. Additionally, transportation companies could register if the transport of materials was required. The tool was primarily utilized in urban areas and larger infrastructure projects (Brinkhoff et al., 2020). However, in 2019, it was determined that the business was not sustainable without external capital, and the tool was decommissioned (Siljevall, 2019).

8.3 Identified digital tools in other countries

8.3.1 VegLCA

VegLCA is a Norwegian tool by Asplan Viak for the Norwegian Public Roads Administration. All projects exceeding NOK 51 million are required to use VEgLCA to calculate GHG emissions (Dahlstrøm Andvik et al., 2022). VegLCA has two parts: an overview tool for early stages without detailed data and a thorough tool for later stages. It aids in planning, tender preparation, and environmental impact calculations of construction activities.

8.3.2 Porfyr

Porfyr is a Norwegian digital marketplace for surplus masses, developed through a collaboration between Bærum municipality, Norconsult Digital, and Norsk Gjenvinning m3 (Daler, 2024). The system connects entities with surplus materials to those needing resources. It is user-friendly and suitable for builders, contractors, advisors, developers, and transporters (Norconsult Digital, 2024). Additionally, it aims to ensure that the transportation of these materials is minimized by considering transport distances, thereby promoting sustainability (Daler, 2024).

8.3.3 DynaRoad

DynaRoad, developed in Finland, helps manage mass in large infrastructure projects through its three modules: Plan, Schedule, and Control. The planning module optimizes mass distribution, the scheduling module creates project timelines, and the controlling module tracks progress against the initial plan (DynaRoad, 2005; Mireé & Nordin, 2014). Topcon acquired DynaRoad in 2013 (Topcon, 2013).

8.3.4 Dutch Soil Passport

The Dutch Soil Passport was established in 2022 by Ledger Leopard in collaboration with various partners, under the guidance of the Dutch Department of Waterways and Public Works (Ledger Leopard, n.d.). Its goal is to enhance soil management practices by providing transparent tracking of soil excavation, transportation, and properties. Utilizing blockchain technology, the information is digitized, reducing paperwork and increasing trust among stakeholders in the soil supply chain (Ledger Leopard, n.d.). The Soil Passport operates on a shared network where each soil transaction is documented and verified. Every stage, from excavation to the destination, is recorded on the blockchain, offering real-time visibility and accountability (Ledger Leopard, n.d.).

8.3.5 TERRASS

In 2012, the French Geological Survey (BRGM) introduced a digital tool called TERRASS for managing the excavated soil network in France (French Geological

Survey, 2024). This tool facilitates the connection between worksite managers and other actors requiring surplus excavated earth, offering a contractual framework for transactions (French Geological Survey, n.d.). The agreement is formalized through a traceability document, which is subsequently transmitted to another system, the Reusable Soils Recording Log (BSTR), to archive and preserve the information. This process also establishes controls and generates monitoring indicators (French Geological Survey, n.d.). Although it is free of charge, the tool is not being used to its full potential, mainly because it is not well-known (French Geological Survey, 2024).

8.3.6 CL:AIRE Register of Material

Intending to create positive environmental and economic impacts by reusing soil within construction and development projects in England and Wales, CL:AIRE designed the Register to assist site managers in connecting projects with material surpluses or shortages (CL:AIRE, n.d.-a). The Register is free of charge and includes project location, quantity available, availability period, and material type (CL:AIRE, n.d.-a). The use of the Register is voluntary, as it supports the CLA:IRE DoW CoP scheme, and the materials listed in Table 2-7 are allowed (Bardos, 2025).

8.3.7 Topcon Magnet Project

Topcon MAGNET Project, an American tool previously known as Magnet Office Mass Haul, combines the functionalities of DynaRoad Plan, Schedule, and Control with those of MAGNET Modeler and Explore (Topcon, n.d.). This tool is designed for mass handling, transport, and production time planning, featuring an optimization algorithm to manage large-scale mass transport projects efficiently and reduce the need for additional tools. It effectively handles large-scale construction projects and provides visualization of mass handling through various chart types. However, it does not incorporate cost calculations, and its complexity may result in a longer acclimation period (Sweco, 2024).

8.3.8 Trimble TILOS & Trimble Business Center – HCE & Trimble-Quantm

Trimble Construction, an American company, owns tools such as Trimble–TILOS, Trimble Business Center-HCE, and Trimble-Quantm (Trimble, n.d.). Trimble – TILOS focuses on production time planning with simplifications for better understanding and quicker adaptation. The most accepted chart types help visualize and control mass handling. It includes a consolidated forecast chart for costs, revenues, and resource use, but lacks an optimization algorithm for mass transport, and is only applicable to individual linear objects (Sweco, 2024). Trimble Business Center-HCE is designed for mass handling and transport, incorporating an optimization algorithm for mass transport. It visualizes mass movements with clear charts and allows data export to TILOS (Sweco, 2024). Trimble-Quantm focuses on preliminary design and corridor analysis, enabling the generation of alternative routes and their evaluation based on cost parameters such as mass handling. It also supports data export to TILOS (Sweco, 2024).

8.3.9 Softree – Optimal

Softree-Optimal is a Canadian digital tool (Softree, n.d.) designed to optimize vertical and horizontal placement based on mass handling and transportation parameters. It includes innovative chart types to facilitate the understanding of mass movements.

However, it lacks the opportunity to effectively schedule mass production handling (Sweco, 2024).

Table 8-2 and Table 8-3 provide a summary of the key benefits of the presented tools, both in Sweden and internationally.

Table 8-2. Summary of the main benefits of identified digital tools in Sweden.

Tool	Main Benefit
Excel-based Prototype Tool	Assessment of project circularity through KPIs and indicators based on input data.
Masscycle	Enables detailed tracking of mass balance and circularity, using KPIs and visualizations for improved project planning.
Mass-portal	Facilitates coordination among TrV infrastructure projects by tracking and managing excavated materials.
Geokalkyl	Analyze alternative alignments of infrastructure projects to optimize mass management and geotechnical reinforcements, reducing costs, energy consumption, and CO_2 emissions.
Klimatkalkyl	Calculating the climate impact and energy consumption of transportation infrastructure projects, using a life cycle perspective.
ELSA	Monitoring of energy and material flows in TrV projects, providing precise tracking of CO_2 emissions and material management.
SmartMass	Evaluation of cost and climate impact for mass management, including a comparison of remediation methods.
GeoBIM	Visualization and reuse of geotechnical data, optimizing excavation and remediation activities, and ensuring traceability and reuse of geotechnical materials.
Pinpointer	Directly matching material supply and demand.
Optimass	Helps municipalities and regions establish mass balances early in the planning process.
GEOSECMA for ArcGIS	Supports municipalities in mass management by streamlining planning processes for construction projects.
Loop Rocks	Connected projects to share surplus materials, enabled the efficient transportation and management of excavated materials, contributing to material savings.

Table 8-3. Summary of the main benefits of identified digital tools in other countries.

Tool	Main Output/Benefit
VegLCA	Calculate GHG emissions for construction projects.
Porfyr	Digital marketplace connecting entities with surplus excavated materials to those in need.
DynaRoad	Optimizes mass distribution in large infrastructure projects; three modules (Plan, Schedule, Control) enable effective management of mass handling.
Dutch Soil Passport	Ensures transparency and traceability in soil management; tracks excavation, transportation, and properties of soil materials through blockchain technology.
TERRASS	Facilitates connection between worksite managers and entities requiring surplus excavated earth; ensures proper documentation and traceability; enhances soil reuse through contractual agreements and monitoring controls.
CL:AIRE Register of Material	Supports the reuse of soil by connecting projects with material surpluses or shortages; provides a free, voluntary platform for site managers to track available materials based on location, quantity, and type.

Topcon Magnet Project	Combines mass handling, transport, and production time planning into one tool; visualizes mass movements with various chart types.
Trimble TILOS	Provides simplified production time planning; visualizes mass handling through charts; helps with cost and resource control
Trimble Business Center – HCE	Optimizes mass transport; visualizes mass movements; enables data export for further planning in TILOS.
Trimble-Quantm	Focuses on preliminary design and route evaluation; aids the generation of alternative routes based on mass handling cost parameters.
Softree – Optimal	Optimizes mass handling and transportation through innovative chart types; assists in vertical and horizontal placement of mass; lacks scheduling capabilities for mass production handling.

9 Identified barriers and possibilities for effective mass management

9.1.1 Barriers and strategies for enhancing the reuse of excavated soil at the EU level

(Hale et al., 2021) outlined the challenges to reusing excavated soil, drawing on both existing literature and the practical insights from the European Large Geotechnical Institutes Platform (ELGIP). Within ELGIP, the "Reuse of Urban Soils and Sites" working group is dedicated to advancing urban soil and site's safe and resource-efficient repurpose. According to the results presented in Table 9-1, the barriers can be categorized into four main areas: (1) regulatory, (2) organizational (project planning and management), (3) logistical, and (4) material quality (Hale et al., 2021).

Table 9-1. Summary of identified barriers for the reuse of excavated soils, from (Hale et al., 2021).

Regulatory Barriers	Organizational Barriers	Logistical and Economic Barriers	Material Quality Barriers
A complicated legislation/regulatory framework that can include both local, regional, and national governments/authorities.	Lack of knowledge and understanding of relevant policy and its application during construction works.	The supply and demand for excavated soil are not always in line (both spatially and temporally).	Rigid geotechnical requirements for soils that are to be reused (e.g., standards for construction materials).
Lack of guidelines for reuse in most countries.	Lack of holistic and early planning for possible reuse (preparation of applications, synergies with other projects, etc.).	Lack of intermediate storage capacity both on- and off-site.	Uncertainty of environmental risk is related to the reuse of lightly contaminated soil. Results in public resistance to reuse.

Long application/permit processing time when reuse is a possible option.	Contracts are not designed to promote the reuse of excavated soil.	Limited permitted intermediate storage time for excavated soil.	Uncertainty about the quality of improved soil. Results in public resistance to reuse. Lack of technical and accepted protocols to show compliance with technical specifications and legislation.
Ownership of reused soil and related risk-responsibility for potential future impacts.		Extra cost for each logistical step (transport to off-site storage, etc.).	Preference for virgin materials.
		Reuse carries no economic incentive when compared to other solutions (e.g., landfilling).	

Based on the above, the authors have proposed strategies to enhance the reuse of excavated soil, aiming to reduce environmental impact and promote sustainability in the construction industry. These strategies emphasize improving regulatory frameworks, encouraging reuse through financial and contractual incentives, optimizing logistical operations, and ensuring the quality of reused soil through standardized documentation and testing (Hale et al., 2021), as summarized in Table 9-2. below.

Table 9-2. Suggested strategies for increasing the reuse of excavated soil, based on (Hale et al., 2021).

Regulation	Regulations on excavated soil reuse should be improved to provide clearer, practical guidelines for planners and constructors. Harmonizing systems within countries and across the EU would promote collaboration and expertise. If cost incentives are insufficient, a landfill tax and evaluation systems rewarding higher reuse levels and sustainable construction practices could be implemented.
Planning process	Addressing reuse early in the planning stages would improve the management of demand and availability, while also enabling the implementation of environmental monitoring programs. Establishing national reuse targets for individual projects and including these requirements in tenders and contracts could greatly enhance soil reuse in construction projects.
Digital logistics systems/soil hubs	Digital logistics systems that monitor the quantities, properties, and types of excavated soil, along with managing supply and demand across various sites, improve project coordination. To overcome storage limitations, the wider implementation of soil hubs (or "soil hotels") could create a more transparent market for supply and demand. Additionally, developing regional and local mass handling plans can facilitate soil reuse by identifying locations for temporary storage and processing, reducing transportation costs, carbon emissions, and time constraints. These plans can also specify methods for transferring excavated soil between sites

Documentation	Documentation is essential for promoting the reuse of excavated soil by confirming its quality and suitability for reuse. Without stricter documentation to ensure that the soil meets geotechnical and geoenvironmental standards, virgin materials may remain the preferred option. Defining specific parameters and standard tests is crucial to integrating into the reuse strategy and ensuring the soil's suitability for reuse.

Furthermore, the report *Excavated Soil Generation, Treatment, and Reuse in the EU* (European Commission: Directorate-General for Environment: Flexman et al., 2024) highlights that stakeholders identified regulatory requirements and treatment costs as the key barriers restricting the treatment and reuse options for excavated soil. These insights, collected through a questionnaire as part of the study supporting the European Commission's Soil Strategy for 2030, see Section 2.3, are presented in Figure 9-1.

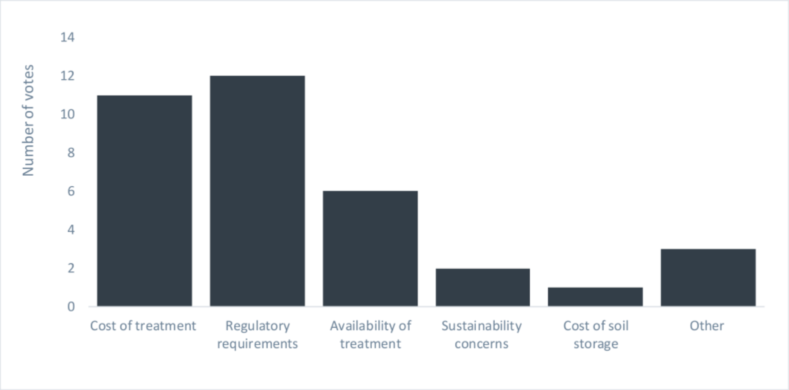


Figure 9-1. Barriers to treatment and reuse options, from (European Commission: Directorate-General for Environment: Flexman et al., 2024).

Similar to the findings outlined above (Table 9-1 and Table 9-2), the report by (European Commission: Directorate-General for Environment: Flexman et al., 2024) provides several key practices for sustainable soil management. These include:

- Reducing soil waste generation (preventing soil degradation, applying practices to stabilize soils, and excavating only the necessary amount of soil);
- Preventing landfilling and using backfilling only when recycling is not feasible (e.g., through bans and targets set in national legislation);
- Assessing the suitability of soil quality for specific reuse (e.g., testing soil for contamination and determining if slightly contaminated soil can be reused in landfill construction, where environmental and human exposure risks are lower compared to landscaping projects);
- Planning, documenting, and verifying the excavation and reuse procedures (e.g., soil passports, material management plans);
- Treating contaminated or compacted soil when possible (additional information would be beneficial to determine the most effective treatment methods);
- Reducing emissions from soil transportation (e.g., reusing on-site, utilizing environmentally friendly vehicles, and minimizing transport distances);

- Linking suppliers with treatment centers and users of excavated soil (e.g., through registers of excavated soils).

Additionally, (Haas et al., 2020) emphasized that the potential for reusing ESR is closely linked to whether these materials are classified as waste. Removing this waste designation is crucial to enable proper treatment. Instead of being viewed as a strict requirement, legislation should be seen as a proactive enabler for ESR treatment. Currently, the EU's fragmented approach, where each country manages site-specific reuse scenarios despite following EU legislation, limits the effective reuse of ESR. To improve this, the authors suggest creating a unified European legal framework, see Figure 7-9, managed by a single authority, to oversee the reuse of excavated materials across all EU countries. This framework would also require construction companies to track and quantify excavated materials, which would help improve the availability of data on ESR. Additionally, the reuse of ESR depends on its geotechnical, mineralogical, and geochemical properties, see Figure 4-9, which need to be standardized and harmonized across different countries (Haas et al., 2020). To reduce landfilling, the authors advocate for a standardized evaluation system within legislation that assesses the economic, environmental, and technical performance of ESR reuse, ultimately leading to a ban on illegal disposal (Haas et al., 2020).

As part of the EU project *"Information-based Strategies for Land Remediation"* (ISLANDR), deliverable 5.1, titled "Spatial Planning Models, Prioritization, and Approaches for Contaminated Soil and Land Reuse (Maring et al., 2024)", examined strategies for maximizing the reuse of excavated soil. The report highlighted as well that the legal status of excavated soil, as defined by the WFD, presents a significant barrier to establishing a circular economy for soil. The waste management principles set in WFD, as discussed in Section 2.1, have significant implications for soil reuse. For instance, reused soils must not cause deterioration of the receiving environment, including ensuring that trace element levels in the reused soil do not exceed the background levels at the receiving site. The authors recommend the establishment of a management system for excavated soil to facilitate its increased reuse. For more information, please refer to (Maring et al., 2024).

9.1.2 Barriers and strategies for enhancing the management of excavated soil in Sweden

The company Massbalans conducted Sweden's largest survey on the management of excavated materials, with 713 participants from the construction industry (Magnusson et al., 2022). The survey, held in September-October 2021, revealed that over 90% of respondents believe recycling faces significant barriers, which have worsened in recent years. Strong support was expressed for simplifying recycling regulations, with 98% of builders and 100% of environmental inspectors in favor. Digitalization was seen as a potential solution, and 93% of respondents advocated for consistent regulation interpretation across Sweden. However, opinions were divided on whether digitalization would effectively streamline the material recycling reporting process (Magnusson et al., 2022).

Furthermore, in the preliminary study by (Andersson-Sköld et al., 2022) interviews were conducted with various stakeholders to identify the main barriers and possibilities for advancing circular mass management. The study highlights the influence of supervisory authorities on the mass management process and the importance of applying for permits early. One significant challenge is material classification, particularly determining contamination levels for use outside the original project (Andersson-Sköld et al., 2022).

The study recommends updating request documents and delivery requirements, as well as processing recycled materials to ensure quality assurance and CE marking. It also calls for greater collaboration across technical fields, early sampling to assess material quality, and focusing on the suitability of materials for various applications rather than use within the same or neighboring projects (Andersson-Sköld et al., 2022).

Another barrier is the lack of coordination in matching materials for both internal and external projects. The study advocates for improved coordination, digital tracking of materials, and regional or national oversight, potentially through TrV (Andersson-Sköld et al., 2022).

To minimize social and ecological impacts, the study suggests reducing machinery use and transport. It also proposes initiating in-situ treatments like phytoremediation early in the planning phase to reduce the excavated material volume (Andersson-Sköld et al., 2022).

Finally, the study recommends adopting a waste hierarchy approach, clearer reporting, financial incentives for higher-value recycling, and results-driven follow-up to promote circular mass management. It also stresses the need for clearer, result-focused tender documents and highlights the crucial role of procurement in guiding consultants and contractors (Andersson-Sköld et al., 2022).

Additionally, the barriers to circular mass management identified in the "*Circular mass management in collaboration*" project (Sweco, 2024), conducted between 2022 and 2024, are summarized in Table 9-3 below.

Table 9-3. Barriers to circular mass management, from (Sweco, 2024). The original table is in Swedish, while the English translations have been provided by the author.

Barrier	Description
Limited and fragmented knowledge about the masses	There are often strict requirements regarding contaminant levels, coupled with significant uncertainties about what can be stored and reused. While data on materials is provided as the basis for contracts, there are limited opportunities to adjust and improve the data as the project progresses.
Time and demand/supply	The demand for the masses doesn't always align with when the masses become available in other projects. At times, there is either not enough time or resources to explore alternative options.
Distance	There is a lack of nearby external projects that can reuse surplus materials, or a lack of awareness about which external projects are available for reuse.
Costs	Costs can hinder circular mass management, with increased expenses associated with long transport distances, intermediate storage, processing, and recycling.
Lack of space	There is a lack of available land for mass handling and insufficient temporary sites within the project areas.
Inflexible legislation and unclear guidance	The lack of adequate decision support in certain areas creates barriers to circular mass management. There is uncertainty surrounding the exemption for using "uncontaminated soil or other natural material excavated in connection with construction activities." Additionally, the guidance remains open to interpretation on several issues, leading to further ambiguity.

Lack of ownership of the problem	The potential multi-actor collaboration system lacks a key actor to take the initiative and assume a leadership role.
Lack of coordination between stakeholders	Link to above. Lack of organizational structure and concrete collaboration initiatives, where roles and requirements are clarified.
Lack of incentives in procurement	It is easier to stick to previous methods rather than innovate. Setting proper requirements becomes challenging when sufficient data is lacking. These requirements might include goals or connections to KPIs, such as climate calculations.
Inflexible support documents and project description	TrV's requirements for contractors can be rigid, limiting the flexibility of projects to explore alternative solutions, such as utilizing collaborative spaces offered by third parties.
Risk – perception and real	There are many unknown factors, including a lack of practical demonstrations of how collaborative spaces can function and how risks can be minimized or managed.
Lack of political drive	There is a lack of political initiative and drive to establish collaborative systems. Collaborative efforts require support in terms of resources, planning systems, strategies, and goals to succeed.

Accordingly, the authors provided several recommendations for improving circular mass management, organized into five main categories: collaboration systems, data and tools, planning and investigation, performance and roles, and assistive technology (Sweco, 2024). Effective collaboration systems are vital for advancing circular mass management. These systems should connect regional plans, facilitate knowledge-sharing, and require political support at the local or regional level. Authorities like TrV should coordinate efforts, while industry organizations can create platforms for knowledge exchange and standardize processes (Sweco, 2024).

Digital marketplace systems are essential for improving coordination among stakeholders, enhancing material use, and reducing the extraction of virgin materials. Shared platforms can aggregate mass management projects, helping stakeholders make better decisions by showing material needs and availability (Sweco, 2024).

Business models for collaboration platforms must be flexible to meet the diverse needs of different projects. Incentives within project goals and contracts are critical to align all parties towards sustainable goals. Contracts should include clear role definitions, circular mass management incentives, and compliance with waste regulations. Early coordination with regional initiatives is also crucial (Sweco, 2024).

Collaboration platforms should be integrated into existing operations like quarries and receiving facilities to reduce transportation distances, lower costs, and minimize environmental impacts. These platforms support a CE and enhance coordination within the construction and waste sectors. Municipalities and stakeholders should develop permanent platforms and business models to encourage their use in contracts and procurements (Sweco, 2024).

To address challenges in material responsibility, pilot projects are recommended. These projects can test cooperation models, develop maintenance routines for collaboration platforms, and optimize circular mass management. The success of pilot projects can demonstrate the economic and environmental benefits, potentially gaining support for wider integration. Additionally, understanding regional conditions and legislative requirements will assist in future planning (Sweco, 2024).

Finally, the workshop "Samverkansarena" organized by TrV and Sveriges Bergmaterialindustri (Sweden's rock materials industry) in January 2025 in Stockholm, Sweden, served as an example of successful collaboration and provided valuable recommendations for advancing circular mass management. The workshop identified two key tracks for requirements: integrating circular products into procurement processes and using climate calculations and CO_2 reductions for setting requirements and incentives (Svedberg & Lundberg, 2025). Key discussions highlighted the need for incentives for contractors and consultants, including establishing competencies in material management and promoting practical guidelines. Certified roles, such as material coordinators, are essential for embedding expertise in planning and construction (Svedberg & Lundberg, 2025). Additionally, addressing circularity issues early in construction is critical for improved coordination, efficiency, and cost reductions. The workshop emphasized the need to scale successful practices quickly by harmonizing material standards, environmental product declarations, and procurement processes (Svedberg & Lundberg, 2025).

10 Examples of good practices within mass management

Several effective practices for promoting soil reuse, both globally and in Sweden, have been identified and are shown in Table 10-1 and Table 10-2. These practices include government-funded research initiatives primarily focused on the construction industry, along with some initiatives supported by the private sector.

Table 10-1. Examples of good practice within the mass management, based on (Bærum Municipality, 2024; City Loops, n.d.; CL:AIRE, n.d.-c; European Commission: Directorate-General for Environment: Flexman et al., 2024; Walsh et al., 2018).

City/Country	**Project/focused on**	**Goals**	**Benefits**	**Organization involved**	**Funded**
Helsinki, Finland	Optimizing the reuse of excavated soil	Improve coordination and distribution of excavated soil	Conserve carbon, minimize economic and environmental costs	City Board, Urban Environment Division	Not stated
Austria	BauKarussell/ Social urban mining	Deconstruction and reuse of building components	Promote sustainable consumption models	Austrian Institute of Construction Engineering (OIB)	Not stated
Sevran, France	Cycle Terre-centered on utilizing locally sourced resources	Establish an industrial process for recycling soil	Reduce soil dumping, cost savings, environmental advantages, increase material availability, support low-carbon urban development, and create local job opportunities	Not stated	EU-funded
France	Innovative excavation techniques	Promote sustainable usage of excavated soil	Foster a CE, recycling, and reusing waste	French Public Works Federation (FNTP)	Not stated
Brussels, Belgium	Transforming excavated soils into building materials	Generate financial value from excavated soil	None mentioned	Not stated	Privately funded
Høje-Taastrup and *Roskilde (Denmark),* *Mikkeli (Finland), Apeldoorn (the Netherlands), Bodø (Norway),* *Porto (Portugal), and Seville (Spain)*	City Loops/ Circular soil handling/ seven EU cities are testing solutions to promote a more circular approach	Identifying possible actions for circular soil handling at different stages of the construction process.	Developed several instruments: Roadmap for sustainable soil management Guidelines for sustainable soil management and assessment of reuse potential of excavated soils: Prognosis predicting future excavated soil production CO_2 calculator for soil	Municipalities of stated cities	EU-funded

Bærum, Norway	Bærum Ressursbank/establish a collaborative arena to solve the handling of surplus masses in the most sustainable way possible	To recycle and use the surplus materials (stone, soil, concrete, asphalt, etc.)	The surplus masses become a resource that has a value that can be reused, rather than being treated as waste	Bærum municipality, with other partners	By the Norwegian Environment Agency and by Bærum municipality
New York City (NYC), USA	NYC Clean Soil Bank/soil exchange designed to keep soil within a city	To enable circular materials metabolism by reusing surplus soil and other clean waste materials	In its first five years, a soil bank in NYC has reused 420,000 tons of sediment, cutting haul distances, diesel fuel use, and CO_2 emissions. It has reduced truck traffic, minimized waste transfer in environmental justice communities, preserved native soil, and boosted local biodiversity. The initiative also enhances carbon sequestration, reduces the need for virgin resource mining, and helps lower the city's ecological footprint.	Municipal government in NYC	Not stated
U.K. and France	ReCon Soil project: focus on developing and implementing three new soil formulas using locally sourced construction waste and agricultural by-products	The project aims to stop the industry from paying for the disposal of waste soil from construction sites in the UK and France.	The project will test new soil formulas in labs and field trials in the UK and France to evaluate their effectiveness and environmental impact. The results will help create guidelines for their application, while also training 200 workers to support the commercialization of reconstructed soils.	University of Plymouth CL:AIRE, Eden Project Learning, The Bureau de Recherches Géologiques et Minières (BRGM), Comité d'Action Technique et Economique (CATÉ), University of East Anglia, University of Le Havre Normandie	European Regional Development Fund via the Interreg France (Channel) England programme

Table 10-2. Examples of research projects and good practices within mass management in Sweden.

Project	***Description***	***Benefit***
Optimass *2014-ongoing*	Described earlier in the text, see Subsections 7.1.1 and 8.2.4	
Mass handling in Norra Djurgårdsstaden *(Masshantering inom Norra Djurgårdsstaden)* *2015-Ongoing*	The Norra Djurgårdsstaden urban development project focuses on local material management, including the recycling of construction rock and contaminated excavated masses through sorting and crushing. Today, a full-scale facility handles contaminated excavated masses, with a permit to sort up to 400,000 tons of material, including hazardous waste. Initially using dry sorting with a 30-40% recycling rate, the facility upgraded in October 2023 to include wet sorting, which increases recycling to 80% by removing fine materials under 1-2 mm (Masslogistikcenter Norra Djurgårdsstaden, 2025).	In 2023: • 300,000 tons of crushed products 34% recycling of contaminated excavated masses 225,000 tons total recycling in MLC 250,000 tons of rock transported by barge 90% of crushing reduces CO_2 (Masslogistikcenter Norra Djurgårdsstaden, 2025)
Energy-efficient and circular mass management in the TRV through external collaboration: Case study of Södertörn *(Energieffektiv och cirkulär masshantering i Trafikverket genom extern samverkan: fallstudie Södertörn)* *2016-2017*	This project aims to investigate opportunities for the TrV to implement coordination areas for mass management. The Södertörn Cross-Connection, along with surrounding municipal development projects, serves as a case study to demonstrate the methodology and highlight the potential for more efficient material usage and transportation reduction (Lekarp, 2023).	The study employed the Optimass calculation model to evaluate material generation, requirements, and the potential benefits of material coordination. Key areas for coordination were identified. The findings indicate that coordinating materials between the Södertörn Cross-Connection and municipal development projects provides societal benefits, including reduced resource extraction, shorter transport distances, lower emissions, and cost savings, when compared to the current practice of each project managing materials independently (Lekarp, 2023).

Re: Source: Circular management of contaminated materials *(Cirkulär hantering av förorenade massor)* *2017-2020*	The project focuses on creating a foundation for the circular management of contaminated masses, addressing environmental and health issues sustainably while benefiting society. It aims to boost contractors' competitiveness by reducing material, transportation, and landfill costs, contributing to a long-term shift in handling contaminated soil in Sweden. Key participants include Chalmers University of Technology, NCC, RGS Nordic, Renova, Anthesis Enveco AB, and municipal and county authorities (Brinkhoff et al., 2020).	A method has been developed to help stakeholders assess whether soil materials are suitable for safe reuse, considering both environmental and health factors. The main conclusion of this work is that enhancing the recovery of contaminated soil masses has the potential to yield significant socio-economic benefits. Various measures have been identified that could effectively encourage the recovery of contaminated soil within society (Rosén et al., 2020).
Lund to Arlöv 4-track project *– Reuse of infrastructure materials in focus* *2017-2023*	The project upgrades an 11 km rail stretch in southwest Sweden from double-track to four-track, with new stations, bridges, and tunnels. It focuses on sustainability, aiming to reuse 40% of materials in the new tracks and 80% on the temporary track. Excavation materials will also be reused, and other sustainability goals include using fossil-free fuels, reducing the climate impact of steel and concrete, promoting biodiversity, encouraging innovation, and utilizing electric vehicles (Larsson & Gammelsæter, 2023).	In 2020, 92% of existing macadam (ballast) was reused onsite, minimizing the need for new materials. Additionally, 325,000 m^3 of surplus earth was managed, with 25% used for noise barriers, 30% for local redevelopment, and the rest sent to Malmö's harbor projects. In 2021, 350,000 m^3 of soil was managed, with 200,000 m^3 surplus, 10% used for noise barriers, and 20% for Malmö harbor projects. 200,000 m^3 has been reserved for future remediation, and 82% of the old macadam was reused (Larsson & Gammelsæter, 2023).
Circular management of masses in construction and infrastructure projects *(Cirkulär hantering av massor i bygg- och anläggningsprojekt)* *2018-2020*	This project aims to foster more circular management of lightly contaminated masses in construction, infrastructure, and land remediation projects through knowledge dissemination. The goal is to reduce the use of virgin soil and rock materials, while also minimizing the amount of excavated masses sent to landfills, ultimately decreasing transport-related activities (Brinkhoff et al., 2020).	The project highlights challenges in mass handling and reuse in construction, focusing on the lack of responsibility and coordination along the value chain at various levels. It proposes technical solutions to improve communication and documentation, as well as address the complications caused by using different analog and digital systems. The project also calls for clearer legislation to simplify the material reuse process, as current permit requirements are lengthy and uncertain (Brinkhoff et al., 2020).

Mass management in Klimatkalkyl *– part of the project “Reduced life cycle impacts of future infrastructure maintenance”* *2018-2022* *(Masshantering i klimatkalkyler)*	The goal has been to establish a foundation for enhancing the Klimatkalkyl (see Subsection 8.1.5) specifically in terms of more accurately estimating energy consumption and climate emissions associated with material handling during the early stages of planning (Liljenström & Björklund, 2022).	Three approaches were analyzed to enhance the Klimatkalkyl estimates of mass management. The most promising approach involves using Geokalkyl (see Subsection 8.1.4) results. The TrV should ensure that both tools, the Geokalkyl and the Klimatkalkyl, are coordinated and use consistent terminology (Liljenström & Björklund, 2022).
Climate-smart mass transport *(Klimatsmarta masstransporter) (KLIMAT)* *2019–2020*	The Skåne County Administrative Board's project aims to improve energy efficiency and reduce carbon emissions in Skåne through better coordination of mass transport. A mapping of surplus materials from 2018 revealed that only a small portion is sent to landfills, with most being used for low-quality purposes like noise barriers or filling. Some surplus materials are also disposed of illegally. The lack of demand for recycled aggregate materials contributes to this issue (Lundberg et al., 2020).	The project also conducted a scenario analysis to assess the impacts of recycling more surplus materials. By recycling up to 24%, the study suggests potential benefits, including a 27% reduction in CO_2 emissions, a 33% decrease in construction costs, and a 23% reduction in the extraction of quarry materials. Additionally, recycling on controlled surfaces could minimize the spread of contaminants (Lundberg et al., 2020).
Entrepreneurs' advice for sustainable mass management *(Entreprenörsråd för en hållbar masshantering)* *2021–2022*	This project aimed to provide practical advice to contractors for achieving more sustainable material management and exploring how digital tools can enhance material handling. The methodology involved gathering information from literature, reports, and websites, in addition to holding workshops with all the project stakeholders (Magnusson et al., 2022).	The outcome includes a set of recommendations for contractors in areas such as improving coordination in the value chain, implementing knowledge-enhancing measures, navigating laws and permits, and exploring economic incentives and business models. The project also identifies various solutions that can support more sustainable mass handling and improve traceability. These include standards for digital messaging, as well as companies' apps, systems, and services (Magnusson et al., 2022).

Business strategies for climate- and resource-efficient logistics systems in mass management *(Affärslogik klimat och resurseffektiva logiksystem för masshantering)* *2021-2022*	This collaborative project, involving Ecoloop, Linköping University, ABT, Åkeriföretagen, Logistikia, and municipalities of Norrköping, Uppsala, and Linköping, along with the TrV's Ostlänken project, focuses on improving resource efficiency, increasing material recycling, and optimizing transportation for mass management by developing a Mass Logistics Center (MLC). The MLC will receive, process, and store materials from various projects to enable recycling (InfraSweden 2030, n.d.).	The project provides municipalities and developers with planning and decision-making support for implementing circular mass management and establishing MLCs (InfraSweden 2030, n.d.).
Mass management -indicators and key performance indicators for reduced climate impact in procurements *(Masshantering -indikatorer och nyckeltal för incitament för reducerad klimatpåverkan vid upphandling)* *2022*	Described earlier in the text, see Section 1.1 and Subsection 8.1.1	
Functional properties of circular materials *(Funktionsegenskaper för cirkulära material)* *2022–2024*	The aim is to explore the feasibility of creating conditions that enable the procurement of unbound materials in construction projects based on their functional properties, rather than relying on specific, descriptive material characteristics (Englund, 2024).	The project's results are expected to enhance the contractors' motivation to use more circular recycled materials. An important result of this project is that the industry agrees that incentives should be created for increased circular management (Englund, 2024).

Circular mass management through collaboration *(Cirkulär masshantering i samverkan)* *2022-2024*	This project aims to develop a proposal for sustainable material management within the TrV by establishing circular material management through stakeholder collaboration around temporary and nearby coordination areas. The project focuses on identifying collaboration forms, business models, operational models, and governance processes for implementing circular material management. The work will involve interviews, workshops, and meetings to ensure collaboration with the industry, municipalities, and authorities (Lekarp, 2023).	The project identified several barriers to circular material management, with collaboration systems being emphasized as crucial for success, see also Subsection 9.1.2. In the absence of established systems, it was stated that TrV has the opportunity to develop its own data-driven tools and enhance project planning to support more effective material management. The project explored adaptable business models for collaboration areas, emphasizing the need for flexibility to accommodate varying project needs (Sweco, 2024).
Material Flows and Indicators for Circular Economy *(Materialflöden och indikatorer för cirkulär ekonomi)* *2023*	The "Material Flows and Indicators for Circular Economy – MICE" research project provides knowledge and insights into material recycling and circular economy as related to Trv’s activities. It explores barriers and opportunities for circulating construction materials, the quantification of material flows, and potential indicators to support TrV’s work in this area. The analysis was focused on materials like steel, concrete, asphalt, and soil (Lekarp, 2023). The project is a collaboration between Ecoloop and Linköping University (Carlsson et al., 2023).	The MFA estimated the inflow, stock, and outflow of materials within road and rail infrastructure. The findings highlight challenges in compiling data due to inconsistencies and a lack of connections between sources. The project also proposed indicators to aid material circulation, stressing the importance of improving data through changes in procurement requirements for recycling and reuse. To accelerate circular construction in TRV’s activities, three key recommendations were made: 1) Develop a circular construction strategy with clear climate benefits, 2) Enhance control and traceability of materials at both the overall and regional levels, and 3) Implement incentives and policies to coordinate projects and scale up circular material flows (Carlsson et al., 2023).
Use of circular materials in road construction *(Användning av cirkulära material i vägbyggnad)* *2024–2026*	The project aims to develop a proposal for a system to test and describe the functional properties of unbound ballast products and circular materials for use in roads, regardless of their origin (SBUF, n.d.).	The system should be used as a basis for mechanistic design. It includes a testing methodology that will ensure a good correlation with real road damage related to the performance of unbound layers (SBUF, n.d.).

Transport-efficient circular mass handling in collaboration *(Transporteffektiv cirkulär masshantering i samverkan)* *Ongoing*	The goal of this PhD project is to present a range of solutions to problem owners (both private and public), addressing issues from a strategic level, such as regional and municipal planning, to an operational level, including logistics solutions, measurement of efficiency in material flows, and traceability throughout the process. The research will focus on the intersection of construction logistics, planning, and policy processes, emphasizing improving transport efficiency for rock and gravel masses by integrating transport logistics with planning processes (Triple F, n.d.).	The project will explore a range of innovative logistics strategies designed to shorten transport distances, increase fill levels, and reduce the total number of transports. Additionally, it will provide a comprehensive system overview that outlines the roles and relationships among stakeholders. This will offer valuable insights into how various innovative logistics solutions are shaped by the policy processes of these stakeholders (Triple F, n.d.).

11 Discussion

In Europe, excavated soil is classified as CDW under the WFD and its waste category definitions (European Parliament and the Council, 2008), along with the detailed categorization provided by the LoW (European Commission, 2000). However, the definitions of CDW vary across EU countries (European Commission, n.d.), leading to discrepancies, including cases where ESR are either included (Blengini & Garbarino, 2010) or excluded (Hiete et al., 2011). In Sweden, multiple legislative frameworks govern the management of CDW concurrently. The Environmental Code defines CDW as waste generated from construction and demolition activities, aligning with the WFD definition and including the excavated soil in the CDW definition (Swedish EPA, 2024a, 2024b).

In 2020, ESR represented about 52% of CDW and 20% of the total waste generated in Europe (Cristóbal et al., 2024). Likewise, in Sweden, the majority of CDW produced that year was also comprised of excavated soil (European Commission: Joint Research Centre: Cristóbal García et al., 2023). The large volume of excavated soil generated is concerning due to its environmental impacts (Peters et al., 2007; van Eldik et al., 2020) and the economically unsustainable management practices, as a significant portion of this waste is still sent to landfills, despite 80% of the excavated masses in Europe being uncontaminated (Eurostat, 2023; Frédéric, 2021). Even so, excavated soil was excluded from both the 70% recovery target for CDW set by the WFD for 2020 and the EU protocol for CDW (Cristóbal et al., 2024; European Commission: Joint Research Centre: Cristóbal García et al., 2023). (Magnusson et al., 2015) argue that the differing definitions of CDW across EU countries lead to considerable uncertainties in CDW management, complicating cross-country comparisons of recycling and material recovery rates (Cristóbal et al., 2024; European Commission, n.d.). This lack of consistency in definitions may help explain why excavated soil is excluded from the EU's targets and protocols for CDW management.

The assessed literature reveals that the most commonly used tool for quantifying the flows of excavated soil is MFA, while LCA is typically employed to evaluate the environmental (and economic- LCCA) impacts of various management options for excavated soil. However, there is untapped potential in using additional methods, such as CBA and MCDA, to also assess the social and economic dimensions of sustainability. One such tool, SCORE (Sustainable Choice Of REmediation), integrates all three sustainability dimensions: economic, environmental, and social (Rosén et al., 2015). Although originally designed for evaluating remediation alternatives for contaminated sites, SCORE offers a transparent and comprehensive assessment of sustainability across these domains. It combines a linear additive model to rank alternatives with a non-compensatory approach to identify unsustainable options. A key benefit of using SCORE in practice is its ability to stimulate important discussions and bring attention to criteria that might otherwise be overlooked, encouraging a more inclusive and well-rounded evaluation through stakeholder involvement (Rosén et al., 2015). By combining methods like CBA and MCDA, a more holistic and sustainable approach to excavated soil management can be achieved, considering a wider range of factors beyond just environmental and economic aspects.

Furthermore, in light of the unsustainable management practices surrounding CDW, including ESR, CE strategies are receiving increasing attention due to their potential to reduce the consumption of virgin material while also decreasing transportation and storage costs (Ritter et al., 2013). According to the reviewed literature, the primary CE management pathways for ESR include preparation for reuse/reuse, recycling, and recovery, all of which align with the WFD waste hierarchy. The reuse approach, in particular, emphasizes the assessment of the geotechnical properties of excavated soil, ensuring that these properties align with the specific requirements of the intended project (European Commission: Joint Research Centre: Cristóbal García et al., 2023; Kataguiri et al., 2019). Additionally, (Haas et al., 2020) introduced a reuse organigram for ESR, highlighting the importance of geological and geotechnical characterization in the reuse process.

Furthermore, recycling ESR can be accomplished through stabilization or by separating the materials into individual components. Techniques involved in this process include screening, sieving, iron removal, washing, and separating components such as clay and silt (Huang et al., 2022). As noted by (Cristóbal et al., 2024; Zhang, Duan, et al., 2020), the recycling rate is primarily influenced by the composition of ESR, especially its particle size distribution. Finally, the recovery strategy, specifically, backfilling, as defined by (Cristóbal et al., 2024; European Commission: Joint Research Centre: Cristóbal García et al., 2023) can essentially be viewed as a reuse of ESR, with the distinction between the two primarily based on specific definitions within the waste hierarchy, making the difference more about classification than actual construction practice. However, it was noted that the definition of backfilling is interpreted differently among EU members, leading to substantial differences in practice across member states, affecting when soil is considered to be recovered, thus, being a product rather than a waste (European Commission: Directorate-General for Environment: Flexman et al., 2024). The European Commission has clarified that backfilling can be considered a recovery operation rather than waste disposal under certain conditions: it must replace virgin materials, meet the necessary specifications for its intended application, and be used in landscaping or engineering projects (European Commission, 2016b). While backfilling can enhance recovery rates, it should be executed with sustainability in mind. For example, using reclaimed asphalt or crushed concrete for backfilling is often more sustainable than using excavated soil, which might have higher ecological value in other contexts. Given the limited guidance on sustainable backfilling practices, prioritizing soil recycling is recommended wherever feasible (European Commission: Directorate-General for Environment: Flexman et al., 2024).

When examining the definitions of CE strategies outlined in the 9R framework, such as those presented by (Kirchherr et al., 2017), it becomes evident that strategies like *Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, and Repurpose* primarily address circularity from a product perspective. These strategies emphasize smarter product use, manufacturing processes, and the extension of product lifespans. In contrast, only the *Recycle and Recover* strategies are directly related to materials in their definitions (Kirchherr et al., 2017). In the context of excavated soil management, as per the aforementioned definitions, it is clear that only *Recycling and Recovery* are applicable since excavated soil is typically treated as a material rather than a product. However, the literature reveals that current research predominantly focuses on preparing for reuse/reuse, recycling, and recovery/backfilling. This gap in understanding how to effectively define and apply CE strategies to excavated soil offers a valuable opportunity for further exploration.

At the EU level, no single treatment option predominates for managing ESR (European Commission: Joint Research Centre: Cristóbal García et al., 2023). For instance, countries such as the Netherlands, Lithuania, Italy, Cyprus, Bulgaria, and Denmark indicated recycling rates exceeding 80%, while others like Latvia, Slovenia, and Ireland reported 100% backfilling (European Commission: Joint Research Centre: Cristóbal García et al., 2023). Overall, the management of excavated soil in EU countries is typically distributed as follows: 35% for recycling, 40% for backfilling, and 25% for landfilling, with no reported figures for preparing for reuse or incineration. However, studies suggest that 100% recycling and reuse of excavated soil are achievable, far surpassing the current recycling rate of 35% and the reuse rate of 0% (European Commission: Joint Research Centre: Cristóbal García et al., 2023). This potential for reuse is further validated by a demonstration project in Denmark, where 90% of excavated soil was prepared for reuse during area development (City Loops, 2020).

It is worth underlining that the distinction between backfilling and reuse is not always clearly defined in the literature. If backfilling is interpreted as a form of reuse within construction activities (Cristóbal et al., 2024; European Commission: Joint Research Centre: Cristóbal García et al., 2023), then, as previously discussed, approximately 75% of excavated soil in the EU could already be considered recovered through recycling and reuse practices. Nevertheless, the absence of reported figures for preparation for reuse may indicate that direct reuse practices may be underrepresented in existing statistics. This is because reuse activities often occur before materials are formally classified as waste (European Parliament and the Council, 2008). Consistent with this, Eurostat only provides data on excavated soil once it has been classified as waste; soil that is directly reused without entering the waste phase is not captured in Eurostat's datasets (European Commission: Directorate-General for Environment: Flexman et al., 2024). Together, these issues highlight the need for clearer definitions, improved reporting systems, and stronger integration of CE strategies to further enhance the sustainable management of excavated soil in the EU.

Moreover, when comparing the management of ESR between Europe and China, it is evident that Europe performs more effectively. In China, 87% of ESR ends up in dumping sites or unregulated landfills, with only a small fraction being reused, primarily for backfilling (Zhang, Duan, et al., 2020). This is particularly significant considering that China was one of the pioneers in adopting the CE concept.

In Sweden, the distribution is approximately 34% for recycling, 33% for backfilling, and 33% for disposal (European Commission: Joint Research Centre: Cristóbal García et al., 2023). However, upon reviewing the literature, it was noted that the Swedish EPA guidelines on the management of excavated masses, referring to soil and excavated materials from construction projects, focus exclusively on recycling as the CE strategy. Reuse and other strategies, such as backfilling, which is mentioned as a management practice in the report by (European Commission: Joint Research Centre: Cristóbal García et al., 2023) are not included in the guidelines. The Swedish EPA provides definitions for key concepts related to the handling of masses. According to the Environmental Code, "recycling" is defined as "taking an action that results in waste being used as a substitute for another material or preparing it for such use, or an action that results in waste being prepared for reuse. Recycling waste is thus a broader concept that includes everything from preparing waste for reuse to energy recovery" (Swedish EPA, 2023). Additionally, the term “preparing waste for reuse” is defined as actions such as checking, cleaning, or repairing waste to enable it to be reused without further treatment. In the Environmental Code, reuse refers to using a product or component that is not waste again to fulfill the same function for which it was originally intended (Swedish EPA, 2023). Preparing something for reuse is considered recycling waste, which is a simpler process when the material is used again for its original purpose (Swedish EPA, 2023). Furthermore, it is stated that in some cases, excavated masses could be subject to preparation for reuse when there is a clear purpose for the material, and this can be done through simpler procedures. For example, asphalt masses (which are considered waste) can be checked for content, or crushed rock (also considered waste) must undergo assessment and control to ensure suitability for reuse (Swedish EPA, 2023). This distinction could explain why the Swedish EPA's guidelines focus only on recycling. It also highlights a potential difference in the interpretation of strategies defined by the WFD and the Swedish Environmental Code, and how this influences the management of excavated soil.

Additionally, when reviewing the literature on the main barriers and strategies for improving the management of excavated soil, it is evident that much of the focus at the EU level is on the reuse of ESR (European Commission: Directorate-General for Environment: Flexman et al., 2024; Haas et al., 2020; Hale et al., 2021), as outlined below. In Sweden, however, the term "circular mass management" is more commonly used (Andersson-Sköld et al., 2022; Sweco, 2024), with a particular focus on recycling (Andersson-Sköld et al., 2022; Lundberg et al., 2020; Magnusson et al., 2022). Nonetheless, in the report by (Sweco, 2024), it is also noted that one barrier to circular mass management is the lack of nearby external projects that can reuse surplus materials, indicating that there is a recognition of the need for greater coordination and reuse opportunities across different projects.

Based on the reviewed literature, the most common barriers to the reuse and management of excavated soil at the EU level include regulatory complexities, such as unclear guidelines, economic disincentives, and concerns about the geotechnical properties and quality of reused soil. These challenges hinder the widespread adoption of excavated soil reuse, despite its potential within a CE framework. To overcome these obstacles, several strategies have been proposed: improving and harmonizing regulatory frameworks across the EU, integrating soil reuse early in the planning process, adopting digital systems and soil hubs for better coordination and logistics, establishing strong documentation and quality control measures, promoting sustainable soil management practices, and developing standardized evaluation systems to assess the viability of reused soil. Sweden shares many of the same challenges as the broader European context, such as regulatory complexity, coordination gaps, and economic disincentives. However, several innovative solutions have been suggested to overcome these barriers, including the adoption of digital systems, collaborative platforms, and financial incentives. Overcoming these obstacles will require coordinated efforts from industry stakeholders, regulatory authorities, and political leaders to drive forward a more sustainable CE in construction and ensure the effective reuse of excavated soil.

As examples of best practices in the management of excavated soil, countries such as the Netherlands, Belgium, France, and the U.K. have made significant strides. Various regulatory frameworks, such as the Standstill Principle in the Netherlands and Belgium, the Fit for Use approach in the Netherlands, and the DoW CoP Scheme in the U.K., have been adopted to facilitate more effective soil management, addressing one of the key barriers – regulatory complexity. In addition, the use of digital tools, such as Soil Passports and material tracking systems in the U.K. and France, supports the implementation of more circular and sustainable practices in managing excavated soil. These initiatives demonstrate a commitment to improving the sustainability and efficiency of soil management processes.

Moreover, the literature highlights the wide range of potential applications for reused excavated soil, including base layers, filling, paving materials, and vegetation covers (Kataguiri et al., 2019; Magnusson et al., 2022). Excavated soil can also be used to produce recycled bricks by mixing recycled clay from the soil with other materials (Zhang, Zhang, et al., 2020). It can be processed into cement-treated base materials by using recycled crushed aggregates (Xu et al., 2022), or incorporated into concrete blocks, replacing natural aggregates with excavated soil or recycled concrete aggregates (Luo et al., 2022). Additionally, excavated soil can be used in the production of geopolymer-based products (Capasso et al., 2021) and cement mortar (Priyadharshini et al., 2019). An innovative approach is combining biowaste with excavated soil, which enhances the sustainability of construction materials by addressing both waste disposal and resource consumption (Scialpi & Perrotti, 2022).

These practices align with the concept of Industrial Symbiosis (IS), which fosters CE principles by facilitating the physical exchanges of wastes, energy, water, and by-products between industries, as well as encouraging shared infrastructure and services (Chertow, 2007). In this context, excavated soil becomes a valuable resource, reducing reliance on virgin materials and promoting a more sustainable construction approach. Such collaborations between industries can help address both environmental challenges and business needs by turning waste generated by one organization into an input for another (Chertow, 2007). As noted by (Chertow & Ehrenfeld, 2012) this approach transforms negative environmental externalities into positive outcomes, contributing to the CE (Genc et al., 2019) and the achievement of SDGs (Domenech et al., 2019; Iacondini et al., 2015).

12 Conclusion

The following main conclusions were drawn from this literature review:

- The definition and classification of CDW vary across EU countries, leading to discrepancies in how materials like excavated soil are categorized and managed.
- Excavated soil management in the EU is divided into three main pathways: recycling, backfilling, and landfilling.
- Methods like MFA and LCA are commonly used to quantify flows and evaluate the environmental and economic impacts of managing excavated soil. Additional tools such as CBA and MCDA could better assess the economic and social dimensions, offering a more holistic view of sustainability.
- CE strategies for excavated soil include preparing for reuse/reuse, recycling, and recovery/backfilling, aligning with the waste hierarchy of the EU WFD.
- A gap exists in the understanding of how CE strategies should be defined and implemented in excavated soil management. Although current research mainly focuses on reuse, recycling, and recovery/backfilling, there is a need for more precise definitions and a more effective application of these strategies to excavated soil.
- There is a notable difference between Sweden's regulatory framework (Swedish Environmental Code) and the WFD in defining CE strategies, particularly regarding reuse and recycling. This discrepancy influences how excavated soil is managed, with Sweden's focus on recycling limiting opportunities for reuse in favor of recycling practices.
- Key barriers to the reuse and recycling of excavated soil in the EU include regulatory complexity, economic disincentives, and concerns about the quality and geotechnical properties of reused soil.
- Strategies to overcome these barriers include harmonizing regulatory frameworks, integrating reuse early in the planning process, adopting digital systems, and promoting better coordination across projects.
- Several countries, such as the Netherlands, Belgium, France, and the U.K., have adopted innovative regulatory frameworks and digital tools that address regulatory complexities and promote more sustainable soil management practices.
- The potential applications of reused excavated soil in construction are vast, including base layers, paving materials, and even recycled bricks, cement-treated base materials, and geopolymer-based products.
- Although several relevant ESR indicators were identified across different methodological domains, no additional or more specialized indicators emerged from the literature. This reveals a clear research gap: the absence of an ESR-specific indicator framework for systematically assessing circularity and sustainability in excavated soil management. To help address this gap, the INDIMASS project will introduce a tool that evaluates the circularity and sustainability of ESR management within infrastructure projects in TrV. Furthermore, the tool will expand its scope by incorporating a broader societal perspective, allowing for a more holistic and comprehensive assessment of these projects.

13 References

Adler, M. D. (2013). Cost-benefit analysis and distributional weights: An overview. *Duke Environmental and Energy Economics Working Paper EE*, 13-04.

Afrin, H. (2017). A review on different types soil stabilization techniques. *International Journal of Transportation Engineering and Technology*, *3*(2), 19-24.

Andersson-Sköld, Y., Norrman, J., Patrício, J., Mirzanamadi, R., & Claesson, J. (2022). *Mass management – indicators and key performance indicators for reduced climate impact in procurements* (VTI Report 1154). S. N. R. a. T. R. Institute.

Andersson, R., & Borre, C. (2024). *Increasing coordination of excavated material between infrastructure projects:*

Creation of a digital platform for the coordination of excavated material at the Swedish Transport Administration [Master Thesis, Chalmers University of Technology]. Gothenburg, Sweden.

Axelsson, M. (2023). *Key performance Indicators for Sustainable and Circular Material Management - Within a municipality in Värmland County* Linneuniversitetet]. https://www.diva-portal.org/smash/get/diva2:1791284/FULLTEXT01.pdf

Bærum Municipality. (2024). *Bærum Resource Bank,* . Retrieved 03-20 from https://www.baerum.kommune.no/politikk-og-samfunn/samfunnsutvikling/om-barum-ressursbank/

Bardos, P. (2025). UK Legislation. In.

Basler and Hofman Ingenieure und Planer. (1974). Studie Umwelt und Volkswirtschaft, Vergleich der Umwelt-belastung von Beha¨ltern aus PVC, Glas, Blech und Karton; . *Eidgenössisches Amt fur Umweltschutz*.

Baumann, H., & Tillman, A.-M. (2004). *The hitch hiker's guide to LCA* (Vol. 1).

Becker, N., Kimhi, A., & Argaman, E. (2020). Costs and benefits of waste soils removal. *Land use policy*, *99*, 104877.

Blanc, C., Darmendrail, D., Rouvreau, L., Boissard, G., & Scamps, M. (2012). *Reuse of excavates soils/tools developed as part of the French soil management framework* III International Conference of CABERNET, Ustroń, Poland.

Blengini, G. A., & Garbarino, E. (2010). Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix. *Journal of cleaner production*, *18*(10-11), 1021-1030.

Boadway, R. W. (1975). Cost-benefit rules in general equilibrium. *The Review of Economic Studies*, *42*(3), 361-374.

Bocken, N. M., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of industrial and production engineering*, *33*(5), 308-320.

Borre, C. (2024). In.

BrainKart. (n.d.). *Concepts and Goals of Sustainable Development*. Retrieved 02-18 from https://www.brainkart.com/article/Concept-and-Goals-of-Sustainable-Development_41133/

Braungart, M., & McDonough, W. (2002). *Cradle to Cradle*. North Point Press.

Braungart, M., & McDonough, W. (2009). *Cradle to cradle*. Random House.

Bringezu, S., & Moriguchi, Y. (2002). Material Flow analysis. In *A Handbook of Industrial Ecology* (pp. 79-91). Edward Elgar Publishing.

Brinkhoff, P., Norin, M., Janmar, L., Garção, R., Larsson, L., Jansson, R., Grandin, J., & Lindberg, J. (2020). *Circular management of materials in construction and infrastructure projects*. m.-o. v. NCC Teknik/ Hållbarhet.

Brown, B. J., Hanson, M. E., Liverman, D. M., & Merideth, R. W. (1987). Global sustainability: Toward definition. *Environmental management*, *11*, 713-719.

Brunner, H., P.; , & Rechberger, H. (2005). *Practical handbook of Material Flow Analysis*. Taylor & Francis e-Library.

Bulletin of Acts. (2007). *Orders and Decrees of the State of the Netherlands 2007 469 Decree of 22 November 2007 containing rules with respect to the quality of soil (Soil Quality Decree, with an ammendment in 2009)*.

Burgman, M. (2005). *Risks and decisions for conservation and environmental management*. Cambridge University Press.

C2C. (2018). Retrieved 01-09 from https://www.c2ccertified.org/about

Capasso, I., Liguori, B., Ferone, C., Caputo, D., & Cioffi, R. (2021). Strategies for the valorization of soil waste by geopolymer production: An overview. *Journal of cleaner production*, *288*, 125646.

Carlsson, A., Dunér, F., & Lundberg, K. (2023). Materialflöden och indikatorer för cirkulär ekonomi: Slutrapport_MICE. In.

Chen, X., Fujita, T., Ohnishi, S., Fujii, M., & Geng, Y. (2012). The impact of scale, recycling boundary, and type of waste on symbiosis and recycling: An empirical study of Japanese eco-towns. *Journal of industrial ecology*, *16*(1), 129-141.

Chertow, M., & Ehrenfeld, J. (2012). Organizing self-organizing systems: Toward a theory of industrial symbiosis. *Journal of industrial ecology*, *16*(1), 13-27.

Chertow, M. R. (2007). "Uncovering" industrial symbiosis. *Journal of industrial ecology*, *11*(1), 11-30.

Chowdhury, S. (2020). *Urban potential in Bio-based Circular Economy*.

City Loops. (2020). *Circular soil handling*. Retrieved 03-21 from https://cityloops.eu/construction-demolition-waste/circular-soil-handling

City Loops. (n.d.). *CDW Replication Package 7, Circular soil handling*. Retrieved 03-20 from https://cityloops.eu/fileadmin/user_upload/RP7-circular-soil-handling.pdf

CL:AIRE. (2024). *Earthbanks: Proof-of-Concept research and demonstration of Soil Management, Storage and Treatment Facilities*. Retrieved 12-15 from https://claire.co.uk/projects-and-initiatives/earthbanks

CL:AIRE. (n.d.-a). *CL:AIRE Register of Materials*. Retrieved 12-15 from https://claire.co.uk/projects-and-initiatives/cl-aire-register-of-materials

CL:AIRE. (n.d.-b). *Definition of Waste: Code of Practice*. Retrieved 12-15 from https://claire.co.uk/projects-and-initiatives/dow-cop

CL:AIRE. (n.d.-c). *ReCon Soil*. Retrieved 02-15 from https://claire.co.uk/projects-and-initiatives/recon-soil

Council Directive 1999/31/EC on the landfill of waste, (1999). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31999L0031

Cristóbal, J., Foster, G., Caro, D., Yunta, F., Manfredi, S., & Tonini, D. (2024). Management of excavated soil and dredging spoil waste from construction and demolition within the EU: Practices, impacts and perspectives. *Science of The Total Environment*, 173859.

Cui, X. (2018). How can cities support sustainability: A bibliometric analysis of urban metabolism. *Ecological indicators*, *93*, 704-717.

Daler, R. (2024). Porfyr – "Tinder" for surplus masses. Retrieved 28-11, from https://anleggsmaskinen.no/2024/02/porfyr-tinder-for-overskuddsmasser/

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., & Ioppolo, G. (2021). A systematic review for measuring circular economy: The 61 indicators. *Journal of cleaner production*, *281*, 124942.

DEAL. (2020). *Circle economy, c40 cities, & biomimicry 3.8. In: The Amsterdam City Doughnut: A Tool for Transformative Action,*. Retrieved 02-24 from https://doughnuteconomics.org/amsterdam-portrait.pdf

Deloitte, D. B. b. (2015). *Construction and Demolition Waste management in Germany,* . https://circabc.europa.eu/ui/group/636f928d-2669-41d3-83db-093e90ca93a2/library/e34c3b4e-c348-4f4e-a0cc-20d42339d7d9/details

Derrible, S., Cheah, L., Arora, M., & Yeow, L. W. (2021). Urban Metabolism. In W. Shi, M. F. Goodchild, M. Batty, M.-P. Kwan, & A. Zhang (Eds.), *Urban informatics* (pp. 85-114). Springer Singapore. https://doi.org/10.1007/978-981-15-8983-6_7

Dictionary. (2010). Oxford Dictionary of English, . In

Ding, Z., Yi, G., Tam, V. W., & Huang, T. (2016). A system dynamics-based environmental performance simulation of construction waste reduction management in China. *Waste Management*, *51*, 130-141.

Division of Environmental Systems Analysis, & Department of Technology Management & Economics. (2024). *Life Cycle Assessment [PoverPoint Slides],* . Chalmers Univeristy of Technology.

Dodgson, J. S., Spackman, M., Pearman, A., & Phillips, L. D. (2009). Multi-criteria analysis: a manual.

Domenech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D., & Roman, L. (2019). Mapping Industrial Symbiosis Development in Europe_ typologies of networks, characteristics, performance and contribution to the Circular Economy. *Resources, conservation and recycling*, *141*, 76-98.

Doughnut Economics Action Lab. (n.d.). *Abought Doughnut Economics*. Retrieved 02-20 from https://doughnuteconomics.org/about-doughnut-economics

Drèze, J., & Stern, N. (1987). The theory of cost-benefit analysis. In *Handbook of public economics* (Vol. 2, pp. 909-989). Elsevier.

Duan, H., & Li, J. (2016). Construction and demolition waste management: China's lessons. In (Vol. 34, pp. 397-398): SAGE Publications Sage UK: London, England.

Duckworth, G. (2011). *The Definition of Waste: Development Industry Code of Practice*. CL: AIRE Publications.

Duden. (2015). Duden: Deutsches Universalworterbuch, eighth ed. Bibliographisches Institut Gmbh,. In

Dupuit, J. (1849). *De l'influence des péages sur l'utilité des voies de communication [electronic resource]*. Carilian-Gœury.

DynaRoad. (2005). *DynaRoad-Manual.*

Ecosystem Evaluation. (n.d.). *Hedonic Pricing Method,*. Retrieved 03-13 from https://www.ecosystemvaluation.org/hedonic_pricing.htm

Ekins, P., Domenech Aparisi, T., Drummond, P., Bleischwitz, R., Hughes, N., & Lotti, L. (2020). The circular economy: What, why, how and where.

Elert, M., Fanger, G., Höglund, L. O., & Jones, C. (2006). *Leachability test for risk assessment of contaminated areas.* https://www.naturvardsverket.se/globalassets/media/publikationer-pdf/ovriga-pub/hallbar-sanering/riskbedomning/620-5535-6.pdf

Elkington, J. (1997). Cannibals with Forks: The Triple Bottom Line of 21st Century Business/Capstone. In: Oxford.

Ellen MacArthur Foundation. (2013). *Towards the circular economy Vol. 1: an economic and business rationale for an accelerated transition,*. Retrieved 01-13 from https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an

Ellen MacArthur Foundation. (2018). *Circular Economy Schools Of Thought*. Retrieved 01-09 from https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Ellen MacArthur Foundation. (2021). *The butterfly diagram: visualising the circular economy,*. Retrieved 02-27 from https://www.ellenmacarthurfoundation.org/circular-economy-diagram

Englund, J. (2024). *Functional properties of circular materials,* . https://vpp.sbuf.se/Public/Documents/ProjectDocuments/55f74314-4ca4-4be8-a86c-f4c27a99f6c8/FinalReport/SBUF%2014184%20Slutrapport%20-%20Funktionsegenskaper%20f%C3%B6r%20cirkul%C3%A4ra%20material.pdf

Eriksson, L., Fredriksson, A., Janné, M., Lundberg, K., Ivanetti, K., Sjöstrand, H., & Kjellsdotter Ivert, L. (2025). *Vad är cirkulär masshantering? En studie om masshanteringssystemets funktioner och aktörer, samt problem och möjligheter för cirkulär hantering.* (VTI rapport 1242 Issue. https://vti.diva-portal.org/smash/get/diva2:2003289/FULLTEXT01.pdf

Esri Partners. (n.d.). *GEOSECMA for ArcGIS*. https://www.esri.com/partners/sokigo-ab-a2T5x00000ACIqjEAH/geosecma-for-arcgis-a2d5x000003mTxxAAE#:~:text=GEOSECMA%20for%20ArcGIS%20is%20a%20commercial%20off-the-shelf%20%28COTS%29,management%2C%20traffic%2C%20digging%20permit%2C%20tree%20inventories%2C%20playground%20inspe

Commission Decision on the European List of Waste, (2000). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02000D0532-20231206

European Commission. (2015). Closing the loop – An EU action plan for the Circular Economy, . *Communication from the Commission to the European Parliament, the Council, the European economic and social committee and the Committee of the regions closing* *the loop. Brussels*, *2*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614

European Commission. (2016a). *EU Construction & Demolition Waste Management Protocol.* https://ec.europa.eu/docsroom/documents/20509/

European Commission. (2016b). *Guidance on the interpretation of the term backfilling.* Retrieved 04-03 from https://fead.be/wp-content/uploads/2022/04/Guidance-on-Backfilling.pdf

European Commission. (2020). A new circular economy action plan for a cleaner and more competitive Europe. *European Commission: Brussels, Belgium*, 1-20.

EU Soil Strategy for 2030 Reaping the benefits of healthy soils for people, food, nature and climate,, (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0699

European Commission. (n.d.-a). *Landfill waste - EU rules aim to limit the amount of waste sent to landfill to the necessary minimum.* Retrieved 01-07 from https://environment.ec.europa.eu/topics/waste-and-recycling/landfill-waste_en

Soil health, (n.d.-b). https://environment.ec.europa.eu/topics/soil-and-land/soil-health_en

European Commission. (n.d.-c). *Soil Monitoring Law.* Retrieved 11-03 from https://environment.ec.europa.eu/topics/soil-health/soil-monitoring-law_en

European Commission. (n.d.). *Construction and demolition waste.* https://environment.ec.europa.eu/topics/waste-and-recycling/construction-and-demolition-waste_en

European Commission: Directorate-General for Environment: Flexman, K., Vu, E., Doyle, H., Thurston, W., Gemmel, L., Cooke, W., & Tyers, J. (2024). *Excavated soil generation, treatment and reuse in the EU – Final report for Task 1.1 of the support study for implementing the EU Soil Strategy for 2030 (09.0201/2022/877182/SER/D.1).* https://op.europa.eu/en/publication-detail/-/publication/2381f59e-2c50-11ef-a61b-01aa75ed71a1/

European Commission: Joint Research Centre. (2023). *Techno-economic and environmental assessment of construction and demolition waste management in the European Union: status quo and prospective potential,* . https://op.europa.eu/en/publication-detail/-/publication/01f8ebe4-b104-11ee-b164-01aa75ed71a1/language-en

European Commission: Joint Research Centre: Cristóbal García, J., Caro, D., Foster, G., Pristerà, G., Gallo, F., & Tonini, D. (2023). *Techno-economic and environmental assessment of construction and demolition waste management in the European Union – Status quo and prospective potential.*

European Parliament. (2023). Circular economy: definition, importance and benefits. https://www.europarl.europa.eu/pdfs/news/expert/2023/5/story/20151201STO05603/20151201STO05603_en.pdf#:~:text=The%20circular%20economy%20is%20a%20model%20of%20production,way%2C%20the%20life%20cycle%20of%20products%20is%20extended.

Waste Framework Directive 2008/98/EC (2008). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02008L0098-20180705

European Union. (2022). *Waste Framework Directive revised*. Retrieved 12-15 from https://circulareconomy.europa.eu/platform/en/news-and-events/all-news/waste-framework-directive-revised

EUROSTAT. (2001). Economy-wide material flow accounts and derived indicators. A methodological guide. *Euro pean Commission, Eurostat, Theme 2, Economy and Finance, 2001.11. 01*.

Eurostat. (2023, 03/09/2024). *Waste statistic, Statistic Explained*. Retrieved 10/09/2024 from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation

Firoozi, A. A., Guney Olgun, C., Firoozi, A. A., & Baghini, M. S. (2017). Fundamentals of soil stabilization. *International Journal of Geo-Engineering*, *8*, 1-16.

Fitz-Gibbon, C. T. (1990). *Performance indicators* (Vol. 2). Multilingual Matters.

Forsman, J., Kreft-Burman, K., Lindroos, N., Hämäläinen, H., Niutanen, V., ;, & Lehtonen, K. (2013). *Experiences of Utilising Mass Stabilised Low-Quality Soils for Infrastructure Construction in the Capital Region of Finland – Case Absoils Project* The XXVIII International Baltic Road Conference,

Frédéric, S. (2021). Excavated soils: The biggest source of waste you've never heard of. Retrieved 11/09/2024, from https://www.euractiv.com/section/circular-economy/news/excavated-soils-the-biggest-source-of-waste-youve-never-heard-of/

French Environment Agency. (2018). *Environment Code Article R.541-8*. Paris, France: French Environment Agency

French Geological Survey. (2024). *Excavated earth: the problem of recovery*. Retrieved 27-11 from https://www.brgm.fr/en/news/article/excavated-earth-problem-recovery

French Geological Survey. (n.d.). *The TERRASS app*. Retrieved 27-11 from https://tex-infoterre.brgm.fr/fr/outils/lapplication-terrass

Froggatt, R. (2023). DoW CoP price rise. Retrieved 2024-12-15, from https://claire.co.uk/projects-and-initiatives/dow-cop

Fura, B., Stec, M., & Miś, T. (2020). tatistical Evaluation of the Level of Development of Circular Economy in European Union Member Countries, . *Energies*, *13*(6401). https://doi.org/10.3390/en13236401

Gadella, M., Van Dreumel, M., & Romjin, R. (2012). Review of 25 years of soil reuse and sustainable land management policies in the Netherlands – finding the balance between environmental protection and the need for recycling.

Garcia-Saravia Ortiz-de-Montellano, C., & van der Meer, Y. (2022). A theoretical framework for circular processes and circular impacts through a comprehensive review of indicators. *Global Journal of Flexible Systems Management*, *23*(2), 291-314.

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production,*, *143*, 757–768. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.12.048

Genc, O., van Capelleveen, G., Erdis, E., Yildiz, O., & Yazan, D. M. (2019). A socio-ecological approach to improve industrial zones towards eco-industrial parks. *Journal of environmental management*, *250*, 109507.

Geng, Y., Zhu, Q., Doberstein, B., & Fujita, T. (2009). Implementing China's circular economy concept at the regional level: A review of progress in Dalian, China. *Waste Management*, *29*(2), 996-1002.

GeoBIM. (n.d.). *What do we mean by GeoBIM and why?* https://www.geobim.se/en

Geoform International. (n.d.). *What are dredge spoils?* Retrieved 01-21 from https://geoforminternational.com/blog/what-are-dredge-spoils/

Girdzijauskaitė, E., Radzevičienė, A., & Jakubavičius, A. (2019). Impact of international branch campus KPIs on the university competitiveness: FARE method. *Insights into Regional Development*, *1*(2), 171-180.

Grubler, A., Bai, X., Buettner, T., Dhakal, S., Fisk, D. J., Ichinose, T., Keirstead, J. E., Sammmer, G., Satterthwaite, D., & Schulz, N. B. (2012). Urban energy systems. In *Global Energy Assessment, Toward a Sustainable Future* (pp. 1307 - 1400). Cambridge University Press. https://doi.org/https://doi.org/10.1017/CBO9780511793677.024

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., & Rydberg, T. (2011). Life cycle assessment: past, present, and future. In: ACS Publications.

Haas, M., Galler, R., Scibile, L., & Benedikt, M. (2020). Waste or valuable resource–a critical European review on re-using and managing tunnel excavation material. *Resources, conservation and recycling*, *162*, 105048.

Hale, S. E., Roque, A. J., Okkenhaug, G., Sørmo, E., Lenoir, T., Carlsson, C., Kupryianchyk, D., Flyhammar, P., & Žlender, B. (2021). The Reuse of Excavated Soils from Construction and Demolition Projects: Limitations and Possibilities. *Sustainability 13*. https://doi.org/ https://doi.org/10.3390/su13116083

Hanley, N., Barbier, E. B., & Barbier, E. (2009). *Pricing nature: cost-benefit analysis and environmental policy*. Edward Elgar Publishing.

Hanley, N., Shogren, J. F., White, B., & White, B. (2001). *Introduction to environmental economics*. Oxford University Press.

Hedenus, F., Persson, M., & Sprei, F. (2018). *Sustainable development: nuances and perspectives*. STUDENTLITTERATUR AB.

Heinonen, J., & Junnila, S. (2011). Case study on the carbon consumption of two metropolitan cities. *The International Journal of Life Cycle Assessment*, *16*, 569-579.

Hiete, M., Stengel, J., Ludwig, J., & Schultmann, F. (2011). Matching construction and demolition waste supply to recycling demand: a regional management chain model. *Building Research & Information*, *39*(4), 333-351.

Holmberg, J., & Larsson, J. (2017). A principles-based framework for sustainability transitions. . The 8th International Sustainability Transitions Conference, Gothenburg.

Hu, J., Xiao, Z., Zhou, R., Deng, W., Wang, M., & Ma, S. (2011). Ecological utilization of leather tannery waste with circular economy model, . *Journal of Cleaner Production,*, *19(2–3)*, 221–228. https://doi.org/ https://doi.org/10.1016/J.JCLEPRO.2010.09.018

Huang, S.-L. (1998). Urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis. *Journal of environmental management*, *52*(1), 39-51.

Huang, T., Kou, S., Liu, D., Li, D., & Xing, F. (2022). Evaluation of the techno-economic feasibility for excavated soil recycling in Shenzhen, China. *Sustainability*, *14*(5), 3028.

Hunkeler, D., Lichtenvort, K., & Rebitzer, G. (2008). *Environmental life cycle costing*. Crc press.

Hunt, R. G. (1974). *Resource and environmental profile analysis of nine beverage container alternatives* (Vol. 91). Environmental Protection Agency.

Iacondini, A., Mencherini, U., Passarini, F., Vassura, I., Fanelli, A., & Cibotti, P. (2015). Feasibility of industrial symbiosis in italy as an opportunity for economic development: Critical success factor analysis, impact and constrains of the specific Italian regulations. *Waste and biomass valorization*, *6*, 865-874.

Indicators, K. P. (2019). Establishing the metrics that guide success (2016). In.

InfraSweden 2030. (n.d.). *Business strategies for climate- and resource-efficient logistics systems in mass management* Retrieved 03-25 from https://infrasweden.nu/wp-content/uploads/2024/08/Affarslogik-klimat-och-resurseffektiva-logistiksystem-for-masshantering_Kristina-Lundberg-Ecoloop.pdf#:~:text=Projektet%20syftar%20till%20att%20ge%20kommuner%20och%20andra,%C3%B6kar%20transporternas%20resurseffektivitet%20och%20hur%20klimat-och%20milj%C3%B6p%C3%A5verkan%20minskar.

International Organization for Standardization. (2024). *ISO 59020:2024*. Retrieved 04-02 from https://www.iso.org/standard/80650.html#:~:text=ISO%2059020%20sets%20forth%20requirements%20and%20guidance%20for,assess%20their%20circularity%20performance%20within%20defined%20economic%20systems.

ISO, I. (2006). 14040 international standard. *Environmental Management—Life Cycle Assessment—Principles and Framework*.

Jansson, O. (2024). Personal Communication. In.

Jansson, O., & Olsson, K. (2024). *Masscycle–A Tool for Circular Project Planning of Sustainable Mass Management* Chalmers Univeristy of Technology].

Johansson, M., & Lundberg, K. (2025). Optimass. In.

Johansson, P.-O. (1993). *Cost-benefit analysis of environmental change*. Cambridge University Press.

Johansson, P.-O., & Kriström, B. (2018). *Cost–benefit analysis*. Cambridge University Press.

John, B., Luederitz, C., Lang, D. J., & von Wehrden, H. (2019). Toward sustainable urban metabolisms. From system understanding to system transformation. *Ecological economics*, *157*, 402-414.

Johnston, P., Everard, M., Santillo, D., & Robèrt, K.-H. (2007). Reclaiming the definition of sustainability. *Environmental science and pollution research international*, *14*(1), 60-66.

Johnston, R. J., Boyle, K. J., Loureiro, M. L., Navrud, S., & Rolfe, J. (2021). Guidance to enhance the validity and credibility of environmental benefit transfers. *Environmental and Resource Economics*, *79*(3), 575-624.

Just, R. E., Hueth, D. L., & Schmitz, A. (2005). *The welfare economics of public policy: a practical approach to project and policy evaluation*. Edward Elgar Publishing.

Kalmykova, Y., Sadagopan, M., & Rosado, L. (2018). Circular economy–From review of theories and practices to development of implementation tools. *Resources, conservation and recycling*, *135*, 190-201.

Kataguiri, K., Boscov, M. E. G., Teixeira, C. E., & Angulo, S. C. (2019). Characterization flowchart for assessing the potential reuse of excavation soils in Sao Paulo city. *Journal of cleaner production*, *240*, 118215.

Keeney, R. L. (1982). Decision analysis: an overview. *Operations research*, *30*(5), 803-838.

Keeney, R. L. (1987). An analysis of the portfolio of sites to characterize for selecting a nuclear repository. *Risk Analysis*, *7*(2), 195-218.

Keeney, R. L., & Raiffa, H. (1993). *Decisions with multiple objectives: preferences and value trade-offs*. Cambridge university press.

Kennedy, C., Cuddihy, J., & Engel-Yan, J. (2007). The changing metabolism of cities. *Journal of industrial ecology*, *11*(2), 43-59.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions, . *Resources, Conservation and Recycling*,, *127*, 221-232. https://doi.org/https://doi.org/10.1016/j.resconrec.2017.09.005

Kirchherr, J., Yang, N.-H. N., Schulze-Spüntrup, F., Heerink, M. J., & Hartley, K. (2023). Conceptualizing the circular economy (revisited): an analysis of 221 definitions. *Resources, conservation and recycling*, *194*, 107001.

Kokubu, K., & Kitada, H. (2015). Material flow cost accounting and existing management perspectives. *Journal of cleaner production*, *108*, 1279-1288.

Konietzko, J., Bocken, N., & Hultink, E. J. (2020). Circular ecosystem innovation: An initial set of principles. *Journal of cleaner production*, *253*, 119942.

KPI.org. (n.d.). *What is a Key Performance Indicator (KPI)?* Retrieved 03-17 from https://www.kpi.org/KPI-Basics/

Krausmann, F., Weisz, H., Eisenmenger, N., Schütz, H., Haas, W., & Schaffartzik, A. (2015). Economy-wide material flow accounting introduction and guide. *Institute of Social Ecology: Vienna, Austria*.

Kwak, S.-Y., & Yoo, S.-H. (2015). The public's value for developing ocean energy technology in the Republic of Korea: A contingent valuation study. *Renewable and Sustainable Energy Reviews*, *43*, 432-439.

Laner, D., Feketitsch, J., Rechberger, H., & Fellner, J. (2016). A novel approach to characterize data uncertainty in material flow analysis and its application to plastics flows in Austria. *Journal of industrial ecology*, *20*(5), 1050-1063.

Larsson, K., & Gammelsæter, E. (2023). Circular materials in infrastructure: the road towards a decarbonised future. *Urban insight*.

Ledger Leopard. (2023). *The first Proof of Concept for the Dutch Soil-passport*. Retrieved 30-11 from https://ledgerleopard.com/projects/the-first-proof-of-concept-for-the-dutch-soil-passport/

Ledger Leopard. (n.d.). *Dutch Soil Passport*. Retrieved 12-07 from https://ledgerleopard.com/case-study-dutch-soil-passport/

Lekarp, F. (2023). *Circularity: Relevant literature – Selection from VTI's search*. https://infrasweden.nu/wp-content/uploads/2024/07/Sammanstallning-av-litteraturlista-om-cirkularitet_juni-2023.pdf

Lesourne, J., & Silvey, A. (1975). Cost-benefit analysis and economic theory. *(No Title).*

Liljenström, C., & Björklund, A. (2022). Masshantering i klimatkalkyler: Förslag till förbättrade beräkningar av masshantering i tidiga planeringsskeden med Trafikverkets modell Klimatkalkyl. In: KTH Royal Institute of Technology.

Lim, S.-Y., Min, S.-H., & Yoo, S.-H. (2016). The public value of contaminated soil remediation in Janghang copper smelter of Korea. *Resources Policy*, *50*, 66-74.

Lindgren, Å., & Moritz, L. (2018). *Geokalkyl Infrastructure - early stages, Methodology description*. Trafikverket.

Ljunge, J., Simoni, M. U., Tofte Husøy, L. J., & Müller, D. B. (2026). Crushing it…? A first national mapping of the Norwegian construction aggregates system using Material Flow Analysis. *Journal of industrial ecology*, 1-14.

Llatas, C. (2011). A model for quantifying construction waste in projects according to the European waste list. *Waste Management*, *31*(6), 1261-1276.

Lundberg, K., Joansson, M., & Frosth, S. (2020). Scenario-och kostnadsanalys av klimatsmarta masstransporter.

Luo, W., Liu, S., Hu, Y., Hu, D., Kow, K.-W., Pang, C., & Li, B. (2022). Sustainable reuse of excavated soil and recycled concrete aggregate in manufacturing concrete blocks. *Construction and Building Materials*, *342*, 127917.

Magnusson, S., Johansson, M., Frosth, S., & Lundberg, K. (2019). Coordinating soil and rock material in urban construction–Scenario analysis of material flows and greenhouse gas emissions. *Journal of cleaner production*, *241*, 118236.

Magnusson, S., Lundberg, K., Svedberg, B., & Knutsson, S. (2015). Sustainable management of excavated soil and rock in urban areas- A literature review. *Journal of cleaner production*, *93*, 18-25.

Magnusson, S., Norin, M., & Grandin, J. (2022). *Entrepreneurs' advice for sustainable mass management*. N. Teknik.

Marella, G., & Raga, R. (2014). Use of the Contingent Valuation Method in the assessment of a landfill mining project. *Waste Management*, *34*(7), 1199-1205.

Maring, L., Vekic, T., Menson, R., Bardos, P., Claudia, N., Sellitri, A., & McLennan, H. (2024). *Barriers & solutions for reuse of contaminated land and soils Information-based Strategies for LAND Remediation Task 5.1 Defining barriers and potential solutions for reuse of contaminated land and soils (PART A) Task 5.2 Strategies for maximizing the reuse of excavated soils (PART B)*.

Martinez-Sanchez, V., Kromann, M. A., & Astrup, T. F. (2015). Life cycle costing of waste management systems: Overview, calculation principles and case studies. *Waste Management*, *36*, 343-355.

Masslogistikcenter Norra Djurgårdsstaden. (2025). *Masslogistikcenter,*. Retrieved 03-27 from https://www.masslogistikcenter.se/sv/

McEvoy, D., Ravetz, J., & Handley, J. (2004). Managing the flow of construction minerals in the north west region of England: A mass balance approach. *Journal of industrial ecology*, *8*(3), 121-140.

Merkhofer, M. W., & Keeney, R. L. (1987). A multiattribute utility analysis of alternative sites for the disposal of nuclear waste. *Risk Analysis*, *7*(2), 173-194.

Ministry of the Environment, O. S. (2011). *Soil, groundwater and sediment standards for use under Part XV.1 of the Environmental Protection Act,*. Retrieved from https://www.ontario.ca/page/soil-ground-water-and-sediment-standards-use-under-part-xv1-environmental-protection-act

Mireé, I., ;, & Nordin, A. (2014). *Mass management in road infrastructure project with the use of a planning software: - A case study of road E22* Högskolan i Halmstad]. https://www.diva-portal.org/smash/get/diva2:731099/FULLTEXT01.pdf

Monier, V., Hesstin, M., Impériale, A., Prat, L., Hobbs, G., & Ramos, K. (2017). Resource efficient use of mixed wastes: Improving management of construction and demolition waste. *European Union*.

Musango, J., Currie, P., & Robinson, B. (2017). Urban metabolism for resource-efficient cities: From theory to implementation. UN Environment. In.

NF X 31-620-2; French Standard. (2018). Paris, France: Association Française de Normalisation

Norconsult Digital. (2024). *Porfyr a "Finn.no for surplus masses" is now being launched.* Retrieved 28-11 from https://norconsultdigital.no/aktuelt/naa-lanseres-porfyr-et-finnno-for-overskuddsmasser/

Norweigan Ministry of Climate and Environment. (2019). *Act on Protection against Pollution and on Waste.* Retrieved from https://www.boutique.afnor.org/standard/nf-x31-620-2/soil-quality-services-related-to-contaminated-sites-and-soils-part-2-requirements-in-the-field-of-investigation-assistance-and-i/article/906749/fa190944

O'Connor, T. (2024). *Sustainability in Amsterdam: A model for Doughnut Economics,.* Retrieved 02-24 from https://growfish.co/sustainability-in-amsterdam-a-model-for-doughnut-economics/#:~:text=In%202020%2C%20Amsterdam%20became%20the%20world%E2%80%99s%20first%20city,for%20future%20resilience%20and%20sustainability%20in%20the%20city.

Odum, H. (1983). Systems ecology: an introduction. In: John Wiley.

Ohlin Saletti, A. (2021). *Infiltration and inflow to wastewater sewer systems,* .

Ortiz-de-Montellano, C. G.-S., Samani, P., & van der Meer, Y. (2023). How can the circular economy support the advancement of the Sustainable Development Goals (SDGs)? A comprehensive analysis. *Sustainable Production and Consumption*, *40*, 352-362.

Oxford English Dictionary. (2024a). uncertainty, n., sense 1.a. In *Oxford English Dictionary*.

Oxford English Dictionary. (2024b). uncertainty, n., sense 2.a. In *Oxford English Dictionary*.

Patel, A. (2019). *Geotechnical investigations and improvement of ground conditions*. Woodhead Publishing.

Personal Communication Maring, L. (2024). Dutch excavated soils regulation. In.

Perth Earthmoving. (n.d.). *The Basics of Earth Moving: What You Need to Know*. Retrieved 03-06 from https://www.perthearthmoving.com/the-basics-of-earth-moving-what-you-need-to-know/

Peters, G. P., Weber, C. L., Guan, D., & Hubacek, K. (2007). China's growing CO2 emissions a race between increasing consumption and efficiency gains. In: ACS Publications.

Pinpointer. (n.d.). *Sustainable process*. Retrieved 11-11 from https://pinpointer.se/hallbar-process/

Plimmer, M. (2023). New Guidance on Classification of Waste Soil from Construction. Retrieved 2024-12-15, from https://www.gea-ltd.co.uk/blog/detail/new-guidance-on-classification-of-waste-soil-from-construction.html

Portugese Environment Agency. (2006). *Decree Law number 178/2006,*.

Portugese Environment Agency. (2019). *Measures and Recommendations to Adopt with Regard to Licensing, Execution Monitoring, Inspection and Examination of Urban Operations—Soil Assessment and Remediation,*. Amadora, Portugal: Portugese Environment Agency,

Prendeville, S. M., O'Connor, F., Bocken, N. M., & Bakker, C. (2017). Uncovering ecodesign dilemmas: A path to business model innovation. *Journal of cleaner production*, *143*, 1327-1339.

Priyadharshini, P., Ramamurthy, K., & Robinson, R. (2019). Influence of temperature and duration of thermal treatment on properties of excavated soil as fine aggregate in cement mortar. *Journal of Materials in Civil Engineering*, *31*(8), 04019137.

Raworth, K. (2012). *A safe and just space for humanity: can we live within the doughnut?* Oxfam.

Restrepo, J. D. C., & Morales-Pinzón, T. (2018). Urban metabolism and sustainability: Precedents, genesis and research perspectives. *Resources, conservation and recycling*, *131*, 216-224.

Ritter, S., Einstein, H., & Galler, R. (2013). Planning the handling of tunnel excavation material–A process of decision making under uncertainty. *Tunnelling and Underground Space Technology*, *33*, 193-201.

Rosén, L., Back, P.-E., Söderqvist, T., Norrman, J., Brinkhoff, P., Norberg, T., Volchko, Y., Norin, M., Bergknut, M., & Döberl, G. (2015). SCORE: A novel multi-criteria decision analysis approach to assessing the sustainability of contaminated land remediation. *Science of The Total Environment*, *511*, 621-638.

Rosén, L., Norrman, J., Söderqvist, T., Nordzell, H., Bergman, J., Hedtjärn, J., Norin, M., Brinkhoff, P., Garcao, R., & Bergendahl, N. (2020). *Circular management of contaminated soil,* .

Rossander, A. (2022). *Classification and Assessment of Soil Materials (Requirements)]* Trafikverket. https://trvdokument.trafikverket.se/

Rugani, B., & Petucco, C. (2025). Environmental benefits of re-using excavated soil flows: The case of Luxembourg. *Science of The Total Environment*, *958*, 177867.

Sakai, S., Yoshida, H., Hirai, Y., Asari, M., Takigami, H., Takahashi, S., Tomoda, K., Peeler, M. V., Wejchert, J., Schmid-Unterseh, T., Ravazzi Douvan, A., Hathaway, R., Hylander, L., Fischer, C., Oh, G. j., Jinhui, L., & Chi, N. K. (2011). International comparative study of 3R and waste management policy developments, . *Mater Cycles Waste Manag*, *13*, 86-102. https://doi.org/https://doi.org/10.1007/s10163-011-0009-x

Sanches, T. L., & Bento, N. V. S. (2020). Urban metabolism: a tool to accelerate the transition to a circular economy. *Sustainable cities and communities*, 860-876.

Sassi, F. (2006). Calculating QALYs, comparing QALY and DALY calculations. *Health policy and planning*, *21*(5), 402-408.

SBUF. (n.d.). *Use of circular materials in road construction,*. Retrieved 03-25 from https://www.sbuf.se/projektresultat/projekt?id=e8f1b3ef-03ca-453e-92b2-8ef2655dd305

Schaltegger, S., & Zvezdov, D. (2015). Expanding material flow cost accounting. Framework, review and potentials. *Journal of cleaner production*, *108*, 1333-1341.

Schönbäck, W., Kosz, M., & Madreiter, T. (1997). *Nationalpark Donauauen: Kosten-Nutzen-Analyse*. Springer.

Scialpi, G., & Perrotti, D. (2022). The use of urban biowaste and excavated soil in the construction sector: A literature review. *Waste Management & Research*, *40*(3), 262-273.

Sennett, R. (1996). *Flesh and stone: The body and the city in western civilization*. WW Norton & Company.

Shen, L. N., & Ma, J. J. (2015). Progress on metabolism of cities, . *Resources Science*, *37*(10), 1941-1952.

Siljevall, A. (2019). NCC discontinues Loop Rocks. Retrieved 2024-11-26, from https://www.byggindustrin.se/affarer-och-samhalle/affarer-i-byggsektorn/ncc-lagger-ner-loop-rocks/

Slovenian Environment Agency. (2008). *Regulation on the Management of Waste Arising from Construction Work,*. Ljubljana, Slovenia: Slovenian Environemnt Agency,

Slovenian Environment Agency. (2011). *Regulation on Burdening of the Soil by Waste,*. Ljubljana, Slovenia: Slovenian Environemnt Agency

Softree. (n.d.). *Earthwork Optimization Add-on for RoadEng*. Retrieved 27-11 from https://www.softree.com/products/optimization

SOILveR. (2022a). *Responses to the questionnaire on Soil Certificates and Soil Passports*. Retrieved 03-05 from https://www.soilver.eu/wp-content/uploads/2022/11/Report_Soil-Cert-and-Passp_221122_annex1.pdf

SOILveR. (2022b). *SOILveR webinar on Soil Certificates and Soil Passports - Short report*. Retrieved 03-06 from https://www.soilver.eu/wp-content/uploads/2022/11/Report_Soil-Cert-and-Passp_-221123.pdf

Sonnemann, G. W., Schuhmacher, M., & Castells, F. (2003). Uncertainty assessment by a Monte Carlo simulation in a life cycle inventory of electricity produced by a waste incinerator. *Journal of cleaner production*, *11*(3), 279-292.

Stahel, W. (2010). *The performance economy*. Springer.

Strid, M. (2024). *ELSA – BEAst: Energiledningssystem för anläggningar - Byggbranschens Elektroniska Affärsstandard– a FEDeRATED LivingLab,* . https://trafikverket.diva-portal.org/smash/get/diva2:1858399/ATTACHMENT14.pdf

Svedberg, B., & Lundberg, K. (2025). *Collaboration Arena – Resource-efficient and circular supply of rock materials – Summary from meeting 22 Jan 2025*.

Svensk Byggtjänst. (2023). *AMA Civil Engineering Works 23 (AMA Anläggning 23)*. Svensk Byggtjänst.

Sweco. (2024). *Circular mass handling in collaboration*.

Swedish EPA. (2010). *Recycling of Waste in Construction Works*. Retrieved 3-12 from https://www.naturvardsverket.se/publikationer/0100/atervinning-av-avfall-i-anlaggningsarbeten---handbok-20101/

Swedish EPA. (2022a). *Management of Excavation Materials and Other Naturally Occurring Materials Suitable for Construction Purposes*. Retrieved 3-12 from https://www.naturvardsverket.se/4ac555/contentassets/510ee48eff174af79e11cadc4e8cecf8/skrivelse-uppdrag-om-hantering-av-schaktmassor-m2021-00191.pdf

Swedish EPA. (2022b). *Guideline Values for Contaminated Soils*. Retrieved 2-12 from https://www.naturvardsverket.se/vagledning-och-stod/fororenade-omraden/riktvarden-for-fororenad-mark/

Swedish EPA. (2023). *Interpretation of key concepts in handling masses* Retrieved 03-21 from https://www.naturvardsverket.se/4acd89/contentassets/f3b0bfba28b84bd6ab9b297bea56cc7b/tolkning-centrala-begrepp-masshantering-23-04-25.pd

Swedish EPA. (2024a). *Construction and demolition waste*. Retrieved 03-21 from https://www.naturvardsverket.se/amnesomraden/avfall/avfallslag/bygg--och-rivningsavfall/

Swedish EPA. (2024b). *Management of construction and demolition waste*. Retrieved 03-21 from https://www.naturvardsverket.se/vagledning-och-stod/avfall/bygg--och-rivningsavfall/#E94844293

Teixeira, J., & Bento, N. (2018). Circular economy, urban metabolism in the future of regional development:"More of the same won't do". Proceedings of the 25th APDR Congress, Lisbon, Portugal,

The Ministry of the Environment. (2011). *Waste Law 646/2011,*. Retrieved from https://www.finlex.fi/sv/laki/alkup/2011/20110646

Toller, S. (2020). *Klimatkalkyl – Calculation of the infrastructure's climate impact and energy use in a life cycle perspective.*

Topcon. (2013). *Topcon acquires DynaRoad, opens new technology center*. Retrieved 11-11 from https://global.topcon.com/news/8154/

Topcon. (n.d.). *Magnet Project*. Retrieved 26-11 from https://mytopcon.topconpositioning.com/na/support/products/magnet-project

Trafikverket. (2021). Presentation of ELSA, excavated masses [PowerPoint presentation], .

Trimble. (n.d.). *A company driven by purpose*. Retrieved 27-11 from https://www.trimble.com/en/about

Triple F. (n.d.). *Transport-efficient circular mass handling in collaboration,*. Retrieved 03-25 from https://triplef.lindholmen.se/projekt/transporteffektiv-cirkular-masshantering-i-samverkan

Tyréns. (n.d.). *This is SmartMass*. Retrieved 10-25 from https://www.smartmass.tyrens.se/smartmass/

UNEA, t. U. E. A., the International Resource Panel and the One Planet network. (2021). *Analysis of the Construction Value Chain*. Retrieved 11/09/2024 from https://www.oneplanetnetwork.org/sites/default/files/value-chain_analysis_-_construction_-_210210.pdf

United Nations. (n.d.). *Sustainable Development Goals*. Retrieved 02-18 from https://www.un.org/sustainabledevelopment/news/communications-material/

United Nations, C. C. (n.d.). *COP 15- Decisions*. Retrieved 02-19 from https://unfccc.int/process-and-meetings/conferences/past-conferences/copenhagen-climate-change-conference-december-2009/cop-15/cop-15-decisions?utm_source=chatgpt.com

United Nations Department of Economic and Social Affairs, P. D. (2024). *World Population Prospects 2024: Summary of Results (UN DESA/POP/2024/TR/NO. 9)*. Retrieved 10/09/2024 from https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/undesa_pd_2024_wpp_2024_advance_unedited_0.pdf

United Nations Department of Economic and Social Affairs, S. D. (n.d.). *The 17 goals*. Retrieved 10/09/2024 from https://sdgs.un.org/goals

United Nations, D. o. E. a. S. A., Population Division (2019). *World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420)*. United Nations. Retrieved 10/09/2024 from https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf

van Eldik, M. A., Vahdatikhaki, F., dos Santos, J. M. O., Visser, M., & Doree, A. (2020). BIM-based environmental impact assessment for infrastructure design projects. *Automation in Construction*, *120*, 103379.

Von Carlowitz, H.-C. (1732). *Sylvicultura Oeconomica Oder Haußwirthliche Nachricht und Naturmäßige Anweisung zur Wilden Baum-Zucht Nebst Gründlicher Darstellung Wie... dem allenthalben und insgemein einreissenden Grossen Holtz-Mangel, Vermittelst Säe-Pflantz-und Versetzung vielerhand Bäume zu rathen... Worbey zugleich eine gründliche Nachricht von dem in Churfl. Sächß. Landen Gefundenen Turff... befindlich* (Vol. 1). Bey Johann Friedrich Brauns sel. Erben.

Walsh, D., Glass, K., Morris, S., Zhang, H., McRae, I., Anderson, N., Alfieri, A., Egendorf, S. P., Holberton, S., & Owrang, S. (2018). Sediment exchange to mitigate pollutant exposure in urban soil. *Journal of environmental management*, *214*, 354-361.

Walsh, D., McRae, I., Zirngibl, R., Chawla, S., Zhang, H., Alfieri, A., Moore, H., Bailey, C., Brooks, A., & Ostock, T. (2019). Generation rate and fate of surplus soil extracted in New York City. *Science of The Total Environment*, *650*, 3093-3100.

Wang, H., Zhang, N., Duan, H., & Dong, L. (2024). Pathways to sound management of excavated soil and rock: A case study in Shenzhen. *Journal of cleaner production*, *458*, 142383.

Watari, T., Böcher, C., Baumgart, A., Ljunge, J., & Wiedenhofer, D. (2025). Mapping sand flows and stocks. *One Earth*, *8*(2).

Weilkiens, T., Weiss, C., Grass, A., & Duggen, K. (2016). Frameworks. OCEB 2 Certification Guide. In: Elsevier.

Whetstone, A., Kalmykova, Y., Rosado, L., & Lavers Westin, A. (2020). Informing sustainable consumption in urban districts: A method for transforming household expenditures into physical quantities. *Sustainability*, *12*(3), 802.

Wikipedia. (n.d.). *Performance indicator*. Retrieved 03-17 from https://en.wikipedia.org/wiki/Performance_indicator

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, *68*, 825-833.

Wolman, A. (1965). The metabolism of cities. *Scientific American*, *213*(3), 178-193.

Xu, M., Ai, X., Huang, L., Fan, L., Yang, J., Pei, Z., Feng, D., & Yi, J. (2022). Utilization of RCAs arising from excavated soil in CTBM: Laboratory characterization and environmental impact assessment. *Journal of cleaner production*, *375*, 134221.

Xu, Z., dos Muchangos, L. S., Ito, L., & Tokai, A. (2023). Cost and health benefit analysis of remediation alternatives for the heavy-metal-contaminated agricultural land in a Pb–Zn mining town in China. *Journal of cleaner production*, *397*, 136503.

Yang, Q., Zhou, J., & Xu, K. (2014). A 3R Implementation Framework to Enable Circular Consumption in Community, . *International Journal of Environmental Science and Development.*, 217-222. https://doi.org/10.7763/IJESD.2014.V5.481.

Yuan, Z. W., Bi, J., & Moriguichi, Y. (2006). The Circular Economy: A New Development Strategy in China. *Journal of industrial ecology*, *10*(1-2), 4-8.

Zeng, H., Zhou, Z., & Xiao, X. (2021). MFCA extension from a life cycle perspective: Methodical refinements and use case. *Resources Policy*, *74*, 101507.

Zhang, N., Duan, H., Sun, P., Li, J., Zuo, J., Mao, R., Liu, G., & Niu, Y. (2020). Characterizing the generation and environmental impacts of subway-related excavated soil and rock in China. *Journal of cleaner production*, *248*, 119242.

Zhang, N., Zhang, H., Schiller, G., Feng, H., Gao, X., Li, E., & Li, X. (2020). Unraveling the global warming mitigation potential from recycling subway-related excavated soil and rock in China via life cycle assessment. *Integrated Environmental Assessment and Management*, *17*(3), 639-650.

Zhou, Z., Zhao, W., Chen, X., & Zeng, H. (2017). MFCA extension from a circular economy perspective: Model modifications and case study. *Journal of cleaner production*, *149*, 110-125.

AI Statement

AI tools were used during the literature review process to support text refinement, including improving clarity, coherence, and academic tone. They were also used to assist in drafting the abstract and in preparing summaries of selected tables. However, these tools did not replace independent reading, critical analysis, or the process of identifying and selecting relevant sources as well as looking for sources.

DEPARTMENT OF ARCHICTECTURE AND CIVIL ENGINEERING
DIVISION OF GEOLOGY AND GEOTECHNICS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY