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An Infrastructure’s emissions assessment tool: AMICO - Account Method of Infrastructures embodied CarbOn

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An Infrastructure's emissions assessment tool: AMICO - Account Method of Infrastructures embodied CarbOn

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Abstract. In 2013, the UK Infrastructure Carbon Review report highlighted how the infrastructure sector contributed to the national total emissions and, therefore, had a key role in contributing to the national reduction, adopting targeted strategies to reduce them. The main objective of AMICO's research project: "Account Method of Infrastructures embodied CarbOn", is the development of a tool for the analysis and parametric evaluation of carbon emissions (Embodied Carbon, EC) and energy resource requirements (Embodied Energy, EE) related to the design and construction of infrastructures (railway tunnels, bridges, highways...) AMICO tool is designed to be used for tendering, contract start-up and construction of infrastructure by Webuild Group (Italian Joint Stock Company) as part of a research project funded by MIMIT - Ministry of Business and Made in Italy, with the scientific support of the Politecnico di Torino (Department of Architecture and Design).

AMICO aims to assess potential impacts in terms of greenhouse gas emissions (GHG) and potential primary energy resource needs over the infrastructure life cycle and at different design process stages, allowing designers and constructors to evaluate decarbonisation in their choices. AMICO is currently organised into two calculation models:

1. An Excel spreadsheet file, divided into worksheets containing algorithms for accounting of EC and EE, organised into two usage models: Basic, which will be used for tenders and the early design stage, and Advanced, which will be used in the detailed design or construction stage.
2. A code for the BIM environment that accounts for impacts (EE and EC) related to infrastructure systems (as defined by UNICLASS) combined and concurrently with design in the BIM environment (this section is not the focus of this paper).

An innovation aspect is sharing a database of environmental data about materials and processes (transportation, construction, demolition) directly related to the Bill of Quantity without using Life Cycle Assessment software. The database will be integrated into the Datalake to speed up and optimise infrastructure design and construction work. You can set the database to the location of the work. Through data digitisation, AMICO is designed to be as automated, easy to fill in, and intuitive as possible.

Keywords: Climate policies, Impact assessment tools, Data digitisation, Infrastructures, Embodied Carbon, Whole-life Carbon assessment tools.

1. Introduction

Since 2010, following the advent of the European Directive on the Energy Performance of Buildings (EPBD) and Nearly Zero Energy Buildings (NZEB) [1], which placed significant emphasis on the importance of reducing energy consumption and adopting renewable energy sources in the building

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sector to mitigate the European Union's energy dependence and reduce greenhouse gas emissions, there has been a succession of regulatory and policy initiatives in the European landscape. This evolution includes the incorporation of the 2015 Paris Agreement [2] and the issuance of the European Green Deal in 2019 [3], culminating in the latest reform packages embedded in the Fit for 55 plan in 2024 [4]. This continuously evolving regulatory context has accentuated the need to address emissions from the construction sector by adopting new European regulatory tools.

This goal implies a comprehensive redesign of critical sectors such as the construction one, identified as one of the main contributors to climate change [5] and responsible for nearly 40% of anthropogenic CO2 emissions [6]. It includes infrastructure, which often utilises materials whose production results in high CO2 emissions, as was already reported in the 2013 British Infrastructure Carbon Review, which highlighted that the infrastructure construction sector was responsible for more than one-sixth of the total emissions in the United Kingdom [7]. In addition, according to the latest data published by the independent American organisation Architecture 2030 about the total annual CO2 emission, it is highlighted that buildings are the most significant contributors to energy resource consumption and emissions during the operational stage, while regarding embodied impacts buildings and infrastructure, with their construction materials, they have approximately the same environmental impacts [8]. These data are unsurprising, considering the large amount of high-impact materials used in infrastructure projects, such as cement, steel, and concrete, and the energy used during the construction phase, almost always deriving from non-renewable sources. In this scenario, taking action to reduce and mitigate environmental impacts is as important in the building as in the infrastructure sector.

There is a growing interest among businesses and economic operators in the construction sector in equipping themselves with adequate tools to quantify and assess energy demand and emissions generated during construction processes. In this regard, Webuild S.p.A., an international company specialising in civil engineering design and construction, initiated a collaboration with the Department of Architecture and Design of the Polytechnic University of Turin in November 2021. This collaboration's objective is to develop a tool for parametric analysis and evaluation of carbon emissions (Embodied Carbon, EC) and energy resource consumption (Embodied Energy, EE) associated with infrastructure design and construction.

The research and development project is named AMICO – Account Method for Infrastructures embodied CarbOn. The tool has been conceived and developed to be used both as an evaluation tool in the bidding phases for construction projects and as a tool for the non-financial reporting of Webuild S.p.A. From this perspective, AMICO is positioned as valuable support for achieving the objectives of transitioning towards a climate-neutral economy.

2. Purpose, Objectives, and Innovation of the Research

The AMICO project aims to meet the need of Webuild S.p.A. for a tool to assess environmental impacts, integrable with its construction project management systems and cost estimation. This article intends to describe the methodology developed for defining the AMICO tool, to calculate the Embodied Energy and Embodied Carbon of infrastructure, and to illustrate its functioning.

The first part will proceed with a methodological description, including the reference standards framework, the indicators considered, the adopted system boundaries, and the data sources used. The second part will present the results obtained by applying the tool to a series of case studies identified in collaboration with the bidding department of Webuild S.p.A. within the company's extensive project portfolio.

The AMICO tool is structured as an Excel model divided into different sheets, available in two modes: a design mode, applicable in the preliminary design phase of bidding, and a construction mode, for bid reordering and construction phases. Data is inputted starting from information on materials (quantities) and equipment (usage hours), obtained from merchandise documents and Bill of Quantities; this type of documentation provides a detailed description of materials, types of work, prices, dimensions, etc., for the construction of an infrastructure based on a contract, derived from construction project management and cost estimation programs. This approach is consistent with international guidelines [9] and ensures good reliability of results.

In summary, the AMICO tool is a calculation model for quantifying the environmental impact of infrastructures, integrable with the software already used by Webuild. Equipped with a dynamic and customisable database, it meticulously considers the construction and installation phase, an aspect often overlooked or generically estimated in other calculation models but of fundamental importance for infrastructure works, where it constitutes a significant portion of the overall impact.

3. Methodology

The methodology of the AMICO tool is structured as follows:

1. State-of-the-art and study of the reference standards;
2. Definition of indicators: Embodied Energy (EE) and Embodied Carbon (EC). In this phase, key indicators for assessing the environmental impact of the infrastructure are identified and defined. Special attention is paid to the embodied energy and carbon emissions associated with the various phases of the artifact's life cycle;
3. Definition of system boundaries: i.e., the phases and modules that constitute the life cycle of the artifact, as defined by EN 17472:2022 Sustainability of buildings - Assessment of the sustainability of civil engineering works - Calculation methods [10] included in the calculation;
4. Definition of functional units by type of infrastructure works;
5. Construction of an integrated database for the model.

Each of these aspects will be examined in detail in the following paragraphs to provide a comprehensive understanding of the methodological approach adopted in the development of the AMICO tool.

3.1. Standards framework

The AMICO tool is based on a national and international standards framework, guidelines, and technical specifications in the construction sector [11,12,13,14,15]. In particular, attention is drawn to the standards EN 17472:2022 "Sustainability of buildings - Assessment of the sustainability of civil engineering works - Calculation methods" [10] and UNI EN 15978:2011 "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method" [16], which outline the phases and modules of the life cycle of an artefact. Both are based on the principles established by ISO 14040:2006 "Environmental Management—Life Cycle Assessment—Principles and Framework", sharing crucial elements such as defining system boundaries and functional units [11]. More specifically, the standard EN 17472:2022 provides a methodology for quantifying the embodied energy and carbon in infrastructure work. It divides the life cycle of an infrastructure into six phases, which are further divided into modules, as illustrated in Figure 1: the modules correspond to activities identified with an alphanumeric code (e.g., A1, A2, and A3). The phases group the modules; for example, the Product phase includes modules A1, A2, and A3.

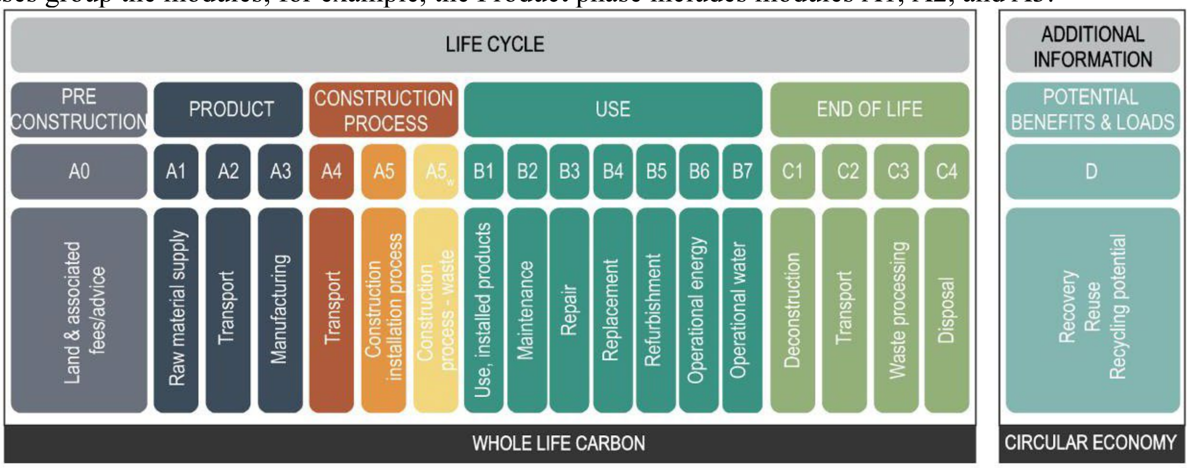

Figure 1 The table shows the life cycle stages for an infrastructure following UNI EN 17472:2022. (authors' elaboration)

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3.2. Indicators

As mentioned before, the indicators used within the AMICO tool are Embodied Carbon (EC) and Embodied Energy (EE). Both have been characterised by the provisions established in scientific and regulatory contexts at the national and international levels [17].

EC represents the carbon dioxide equivalent (CO2eq) emitted, stored, removed, and offset during one or more phases of the life cycle of a specific good, whether it be a product, a building, or an infrastructure. This indicator represents the global warming potential (GWP) of greenhouse gases over a 100-year time horizon.

On the other hand, EE indicates the primary energy resources (renewable and non-renewable) utilised in one or more phases of the life cycle of a specific good, again concerning products, buildings, or infrastructures, and normalised to an appropriate functional unit. The unit of measurement for EE is commonly expressed in kilowatt-hours (kWh) or megajoules (MJ).

3.3. System boundaries

The accounting of the indicators has been developed from a Whole Life Carbon perspective, assuming a reference time horizon, by technical regulations, equal to 120 years [15]. However, at the current stage of development, the AMICO tool has undergone a validation phase through application to a selection of case studies, followed by the analysis of results, with particular attention to the following modules:

- A1-A3: Product; the product stage encompasses three modules: A1 - resource extraction (energy and raw materials); A2 - transport; A3 - transformation into finished and semi-finished products to be delivered to the building site. In the Product stage, the calculation involves summing the quantities of materials and multiplying them by their respective specific emission factors;
- A4: Transport; The EC accounting of module A4 aims to determine the impacts of transport operations on the construction site of materials, products and equipment to the infrastructure construction site. The calculation of this stage depends on various factors, including load, distance, transportation method, type of vehicle used, number of trips made, and finally, the fuel type. Based on the latter, the total fuel consumption of the vehicle(s) is multiplied by a specific emission factors;
- A5: Construction; Module A5 encompasses all construction operations conducted at the construction site utilising off-road equipment and vehicles (unsuitable for road use). The data for executing the EC includes the type of equipment employed, usage hours, and fuel consumption per vehicle. Webuild Group has provided specific information to facilitate the EC accounting. The total fuel used is multiplied by the specific emission factor to obtain the $kgCO_{2eq}$;
- A5w: Construction waste (A5Waste); Module A5w is a specific module devoted to accounting for the EC impact due to construction waste. It is considered an integral part of A5, i.e. the emissions generated by the potential waste produced on the construction site (scraps, debris, damaged products, ...). The calculation involves applying a production correction factor (fPro) to the material effectively used for the construction. Thus, the correction factor assumes a larger material quantity delivered since part of it will be disposed of;
- B4. Use and replacement; this module, relating to the use of the infrastructure, includes removing some materials and products, due to functional obsolescence, and their complete replacement. The replacement frequency (RF) is calculated based on the ratio between the infrastructure’s reference time scenario and the material's expected life.

The remaining modules will be subject to implementation and subsequent validation in future research projects.

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3.4. Functional Unit

According to the principles of the Life Cycle Assessment methodology [11], the results obtained must be normalised concerning a standard functional unit. This approach ensures valid and meaningful comparisons with similar projects, enabling an accurate and transparent assessment of the environmental impact of the considered infrastructures.

The guidelines outlined by the Royal Institution of Chartered Surveyors (RICS) [9] provide a detailed list of appropriate functional units for various infrastructures. In this regard, Table 1 presents a summary of the main types of infrastructures (first column) alongside their respective functional units (second column). However, it is essential to note that evaluators can adopt alternative normalisation units if deemed appropriate. For example, "per bed" could be used for hospitals, while "per student" could be used for schools. This flexibility allows for tailoring the assessment process to the specific needs of the considered context.

Table 1 The functional units for the Embodied Carbon account for several infrastructures following RICS guidelines.

Infrastructures Project Types	Functional unit
roads, runways and bridges	**$kgCO_2e/m^2$** of surface area
railways	**$kgCO_2e/km$** of track installed
tunnels, wells and boreholes, dams and reservoirs	**$kgCO_2e/m^3$** of internal volume
wastewater treatment works, water treatment works, pipelines, waterway works	**$kgCO_2e/m^3$** per minute

3.5. Database and assessment

The AMICO tool has been designed to be used from the early design stages. For this purpose, a database has been included providing the emission factors of EE and EC for the production phase of a series of materials considered key in Webuild's projects. These key materials were identified through a shared analytical process with Webuild, which examined the quantities of resources and raw materials used in relevant infrastructure categories.

The AMICO database stands out for its flexibility and adaptability, as it allows data customisation based on the geographical context of material production, considering each country's specific electricity production methods (energy mix). Additionally, users can integrate additional generic data (from various databases) or specific data (where available, such as Environmental Product Declarations - EPDs or other product labels).

Each key material is associated with a unique identifying code, which allows AMICO to recognise and import it into the tool's processing window. Each identifying code is linked to a material type connected to the database providing the EC and EE production values.

The assessment of EC and EE considers the processes involving key materials during the production phase and their integration into the infrastructure. These processes include on-site transportation, processing, and installation. EE and EC unit values are available for each of these processes, which can be customised based on specific circumstances, such as distances travelled, type of transportation, estimated working hours, and equipment used.

Once the indicators, system boundaries, functional units, and key materials are defined, some algorithms have been integrated into the tool based on national and international technical-scientific references [9, 17, 18, 19]. Figures 2 and 3 show examples of the data display windows of the tool, corresponding to the production phases (A1-A3) and construction phase (A5) in the design calculation mode.

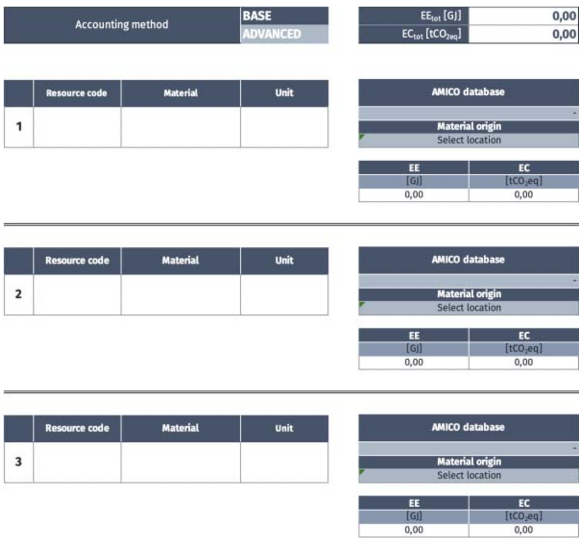


Figure 2 The A1-A3 section of the tool is organised into numbered horizontal sections, each aimed at characterising a material identified from Merchandising or Bill of Quantities documents. Specifically, on the left side, the material is described, including the code that identifies it (*Resource code*), the name of the material (*Material*), and the total quantity referring to the unit of measure (*Unit*). On the right side, the material is characterised by associating it with material from the integrated database (*AMICO database*) and indicating its place of origin (*Material origin*) by choosing from a predefined list of geographical areas. Choices are made using dropdown menus.

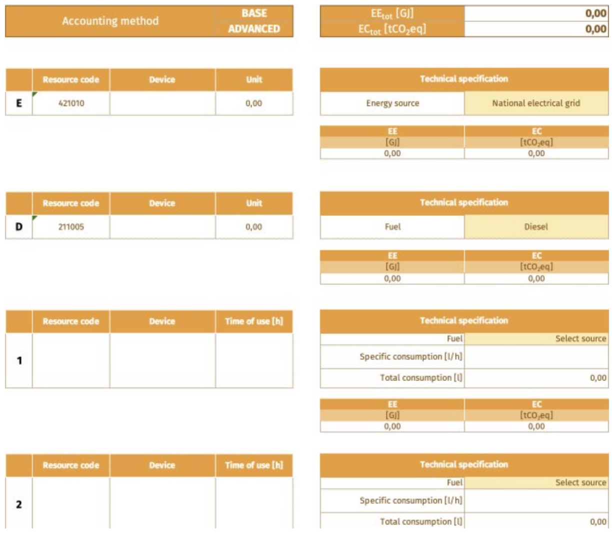


Figure 3 The A5 tab of the tool follows the same horizontal structure and is dedicated to characterising the machinery used for processing. The first two sections identify the total energy resources used, diesel and electricity. From the third section onwards, the machinery is characterised and described by code (Resource code), name of the machinery (Device), and usage time expressed in hours (Time of use [h]). On the right side, the technical specifications of the machinery are pre-filled and automatically assigned from the machinery database provided by the Webuild group. The only action required from the user on this tab is to choose the machinery's fuel type.

4. Case study

Several case studies have been analysed and evaluated to demonstrate the validity of the methodology of the AMICO tool; the following paragraphs present the obtained results. The case studies presented in this work mainly concern the construction of new railway lines, which may include various types of structures such as tunnels, bridges, and open sections. The data used are aggregated and do not allow for distinguishing the relative impact of each type of structure. Therefore, the results should not be considered reference values for individual railway infrastructures but general indications for complex infrastructure projects.

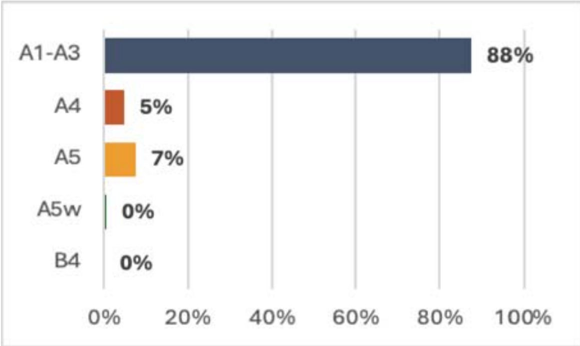
Additionally, although the AMICO tool can provide results for both EE and EC values, it is specified that, for this discussion, only the EC results are discussed and analysed.

For each case study, the following are provided:

- A summary table describing the case study, highlighting: the project location, dimensional and typological characteristics, and the total EC results both in absolute terms and normalized to the functional unit.
- A bar chart illustrates EC's contribution for each phase relative to the total result.

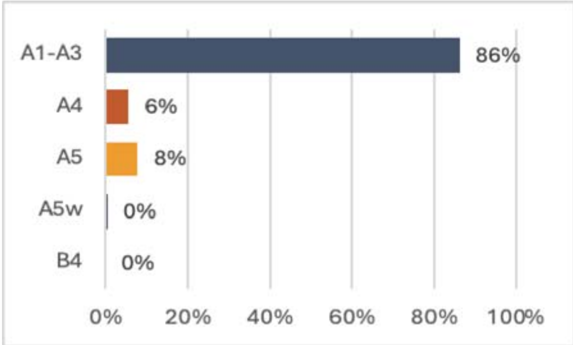
4.1. *Case study 1*

Project Parameters	**Values and unit**
Location	Italy
Infrastructure type	Railway
Length	30 km
Functional unit	km
RESULTS	
Embodied Carbon tot	**1.373.895,86** tCO_2eq
Embodied Carbon f.u.	**47.285,28** tCO_2eq/km



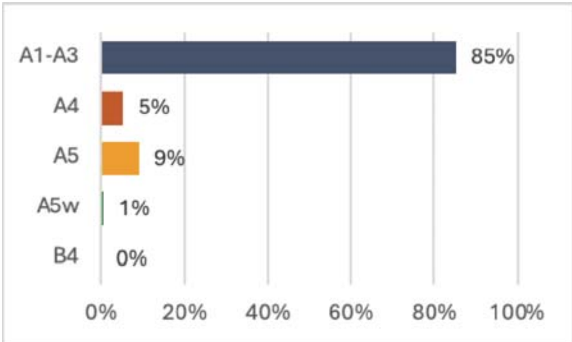
4.2. *Case study 2*

Project Parameters	**Values and unit**
Location	Italy
Infrastructure type	Railway
Length	47 km
Functional unit	km
RESULTS	
Embodied Carbon tot	**1.453.128,22** tCO_2eq
Embodied Carbon f.u.	**31.845,90** tCO_2eq/km



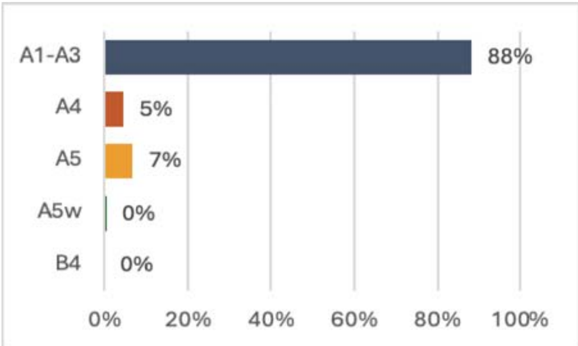
4.3. *Case study 3*

Project Parameters	**Values and unit**
Location	Italy
Infrastructure type	Railway
Length	27 km
Functional unit	km
RESULTS	
Embodied Carbon tot	**1.157.196,78** tCO_2eq
Embodied Carbon f.u.	**44.309,00** tCO_2eq/km



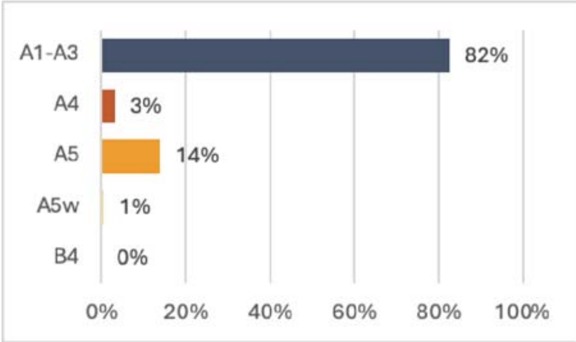
Case study 4

Project Parameters	**Values and unit**
Location	Italy
Infrastructure type	Railway
Length	14,6 km
Functional unit	km
RESULTS	
Embodied Carbon tot	**629.980,34** tCO_2eq
Embodied Carbon f.u.	**44.459,91** tCO_2eq/km



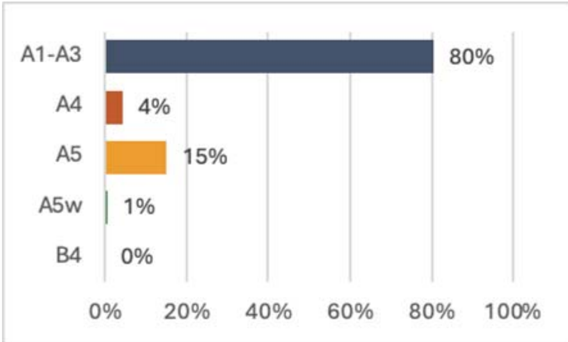
4.4. Case study 5

Project Parameters	Values and unit
Location	Italy
Infrastructure type	Railway tunnel
Length	27 km
Functional unit	km
RESULTS	
Embodied Carbon tot	**1.166.443,10** tCO_2eq
Embodied Carbon f.u.	**44.488,66** tCO_2eq/km



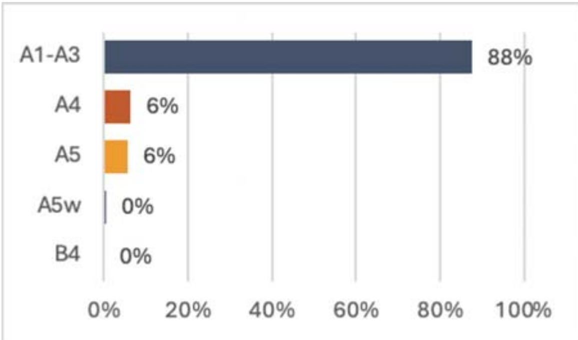
4.5. Case study 6

Project Parameters	Values and unit
Location	Italy
Infrastructure type	Railway
Length	11,8 km
Functional unit	km
RESULTS	
Embodied Carbon tot	**319.882,12** tCO_2eq
Embodied Carbon f.u.	**27.754,31** tCO_2eq/km



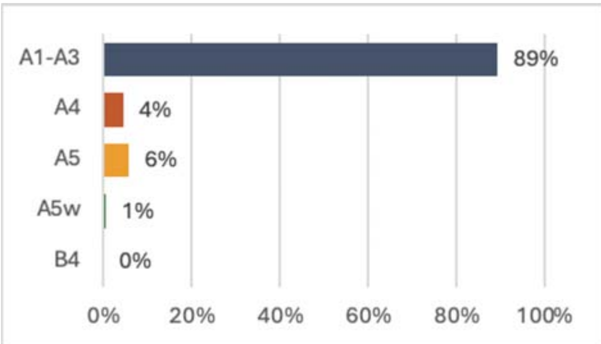
4.6. Case study 7

Project Parameters	Values and unit
Location	Italy
Infrastructure type	Railway
Length	17,9 km
Functional unit	km
RESULTS	
Embodied Carbon tot	**61.332,82** tCO_2eq
Embodied Carbon f.u.	**3.485,65** tCO_2eq/km



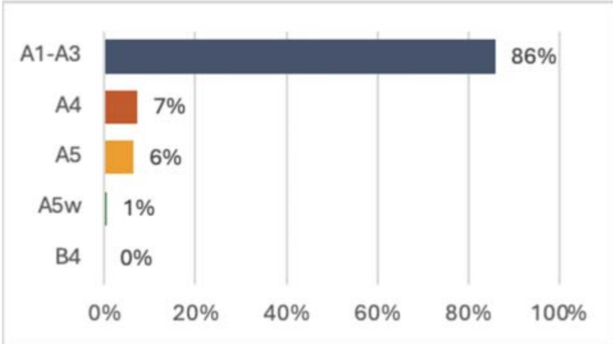
4.7. Case study 8

Project Parameters	Values and unit
Location	Italy
Infrastructure type	Natural tunnel
Length	11 km
Functional unit	km
RESULTS	
Embodied Carbon tot	**885.609,96** tCO_2eq
Embodied Carbon f.u.	**83.078,11** tCO_2eq/km



4.8. *Case study 9*

Project Parameters	**Values and unit**
Location	Italy
Infrastructure type	Railway
Length	35 km
Functional unit	km
RESULTS	
Embodied Carbon tot	**885.609,96** tCO_2eq
Embodied Carbon f.u.	**83.078,11** tCO_2eq/km



4.9. Results discussion

Among the nine illustrated case studies, case No. 8 shows the highest EC impact with 80,510 tCO_{2eq}/km, while case No. 7 exhibits the lowest impact with 3,407.38 tCO_{2eq}/km. The latter has a significantly lower impact due to the adopted construction methodologies. Specifically, the project involves the construction of extensive railway sections on natural terrain, minimising the consumption of materials and energy resources compared to situations involving tunnel sections. The construction of underground sections requires considerable energy resources and materials, contributing to a higher overall environmental impact.

In all cases, the highest impact was observed in the Product phase (A1-A3), which accounts for an average of 85.77%. The Transport module (A4) is the second highest contributor in most cases, with an average incidence of 5.4%, followed by the Construction module (A5). Exceptions are cases No. 5 and No. 6, where the impact of these two modules is inverted: the Transport module (A4) accounts for 3-4%, while the Construction module (A5) accounts for 14-15%. Generally, the Construction waste (A5w) and Replacement (B4) modules can be considered negligible. Specifically, due to the nature of the analysed materials, primarily cement, aggregates, steel, and concrete, all of which are structural elements of the infrastructure, the Replacement module B4 yields an EC impact of 0.00. It occurs because structural elements are assumed to have a service life equal to the reference temporal scenario (120 years [15]) and are not subject to replacement during the infrastructure's service life.

Among the three materials considered as key materials, steel had the highest EC impact, accounting for 48%, followed by cement at 33% and concrete at 19%.

Below are two images: the first, Figure 4, displays the total and normalised results per functional unit [km], divided for each life cycle module included in the calculation. The second image, Figure 5, provides a graphical representation of the results of the nine analysed case studies.

	A1-A3		A4		A5		A5w	
PROJECT	EC tot	EC/f.u.	EC tot	EC/f.u.	EC tot	EC/f.u.	EC tot	EC/f.u.
	tCO_2eq	tCO_2eq/km	tCO_2eq	tCO_2eq/km	tCO_2eq	tCO_2eq/km	tCO_2eq	tCO_2eq/km
Case study 1	1.202.232,16	40.074,41	63.895,59	2.129,85	101.632,69	3.387,76	6.135,43	204,51
Case study 2	1.252.559,94	26.650,21	81.421,02	1.732,36	112.791,27	2.399,81	6.355,99	135,23
Case study 3	986.049,66	36.520,36	63.895,59	2.366,50	101.632,69	3.764,17	6.135,43	227,24
Case study 4	555.574,90	38.053,08	29.200,15	2.000,01	42.397,64	2.903,95	2.807,64	192,30
Case study 5	962.746,19	35.657,27	35.851,35	1.327,83	161.373,96	5.976,81	6.471,60	239,69
Case study 6	257.020,51	21.781,40	13.302,32	1.127,32	48.191,66	4.084,04	1.367,64	115,90
Case study 7	53.703,74	2.983,54	3.926,02	218,11	3.432,91	190,72	270,16	15,01
Case study 8	790.760,15	71.887,29	39.791,18	3.617,38	50.676,49	4.606,95	4.382,15	398,38
Case study 9	1.694.819,21	48.423,41	142.045,94	4.058,46	125.558,53	3.587,39	8.832,75	252,36

Figure 4 The table summarises the total and per functional unit results obtained by applying the AMICO model to the nine case studies. The image depicts partial results regarding Embodied Carbon (EC) concerning different life cycle stages (A1-A3, A4, A5, and A5w).

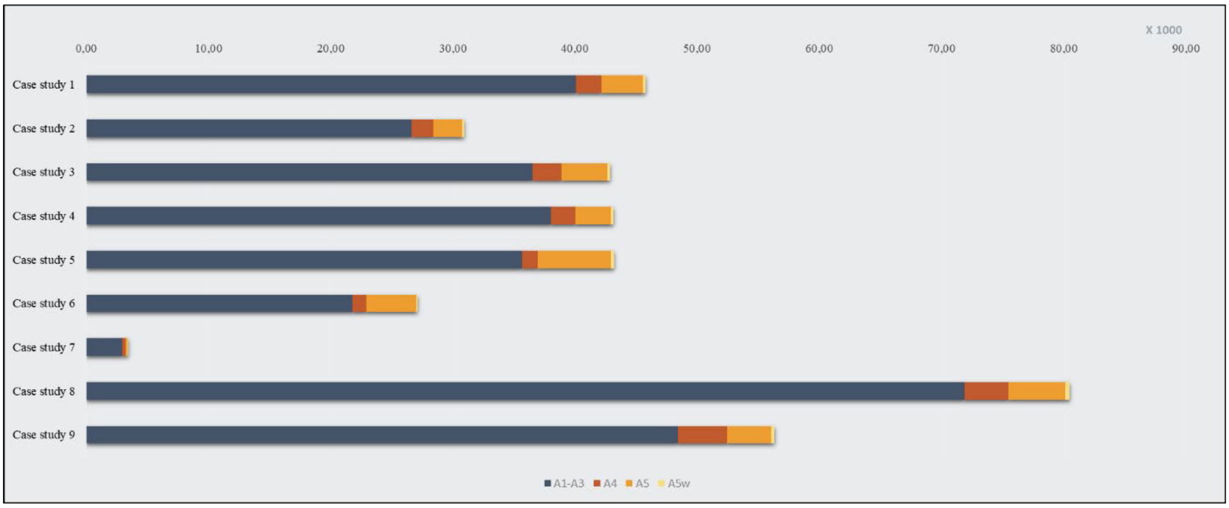


Figure 5 The figure is a graphical representation of the total results of the nine analysed case studies, where bar charts are divided based on the contribution of each life cycle stage to the total impact.

The presented data shows that the normalised EC values per functional unit are heterogeneous and do not allow for a straightforward comparison between infrastructures. This variability highlights the complexity of EC calculation and can be attributed to several factors, including:

- Infrastructure types: The case studies encompass a variety of infrastructure works, including tunnels, bridges, and open-air sections. Each type has distinct characteristics that can significantly influence the overall results.
- Construction techniques: Even within the same type of infrastructure, the construction techniques employed can vary considerably. For instance, a tunnel can be constructed using natural excavation or mechanised methods, leading to different energy requirements and associated on-site processing activities, resulting in different EC values.
- Material sourcing: The origin of construction materials impacts both the Production phase (A1-A3) and the Transport module (A4). Materials extracted and processed in different geographical areas may be associated with markedly different emission factors (due to production methods and the energy mix generating electricity) and require increased fuel consumption for transportation to the construction site.

5. Conclusions

The application of the AMICO tool to the case studies presented in this work has demonstrated its functionality and the effectiveness of the developed methodology. The obtained results confirm the model's ability to fulfil its purposes, namely to provide a valuable tool from the early stages of design for quantifying and assessing the impacts of various types of infrastructure works in terms of the entire project and the established functional unit.

A key strength of the AMICO model lies in its breakdown of results for individual phases of the infrastructure's life cycle. This feature enables understanding the contribution of each phase to the overall impact and identifying areas for improvement to optimise the project in terms of emissions.

Furthermore, the dynamic database integrated into the model allows for calculations even without specific data, making it a flexible tool for various project stages. The application of the model to real case studies has also highlighted the importance of an analytical assessment of the construction phase (A5), as its impact can vary considerably between different infrastructure projects.

In a context where the scientific literature still presents few tools specifically dedicated to assessing the environmental impacts of infrastructure construction, the AMICO model emerges as an innovative contribution to the field.

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