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Roads, homes, and power plants

A disaggregated hybrid multi-regional input-output model to reveal climate impacts of EU construction sectors

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Abstract

The construction of our built environment is a major driver of global material use, greenhouse gas emissions, and their impacts on people and ecosystems. Nevertheless, there is a critical gap in understanding which purposes of construction activity drive these environmental impacts. To yield a detailed yet comprehensive and consistent representation of construction in the global economy**,** this research project proposes a multi-unit approach that expands the construction industry in multi-regional input-output tables. Focusing on the European Union, the project offers insights into the climate impacts of five different construction subsectors (buildings, roads, railways, electricity infrastructure, other civil engineering) by integrating bottom-up data on 14 materials used in the construction of 17 types of structures. Key findings of this disaggregation include: 1) The carbon footprint of construction increases with detailed input resolution. 2) Building construction dominates the carbon footprint of construction in most EU countries, but metal- and material-intensive civil engineering is more carbon-intensive than building construction. 3) Electricity and railway infrastructure relies more on outsourced emissions than building and road construction. The exploration of integrating bottom-up information on buildings and infrastructure from material stock analysis, life cycle inventories, and geographic information systems with economic statistics highlights future avenues for research on physical flows, as well as calls for a further standardisation and harmonisation of detailed national accounts. The developed procedure can have broader applications, benefiting urban planning, consumption footprint assessments, and scenario analyses aligned with international climate goals.

Table of Contents

Abbreviations

EEIOA – environmentally extended input-output analysis
EU – European Union
IOT – input-output table
LCA – life cycle assessment
MRIOT – multi-regional input-output table
MSA – material stock analysis

1. Introduction

1.1. Relevance of detailing construction activities in MRIOT and research aim

The construction of our built environment is a major driver of global carbon dioxide (CO_2) emission which poses a challenge to sustainable development within the remaining carbon budget. Estimates of the carbon footprint of construction range from 10% to 23% of global emissions (Hertwich & Peters, 2009; Huang et al., 2018; International Energy Agency, 2023), while construction activities continue to pose high stakes in face of rising incomes, an aging infrastructure and climate change mitigation and adaptation (Fuldauer et al., 2022; Kikstra et al., 2021; Klaaßen & Steffen, 2023; Zhong et al., 2021).

The lack of comprehensive knowledge on the societal-scale production technology –i.e. on material, service, and labour inputs– to different components of the built environment impedes effective prioritisation and targeted policy design for the diverse actors of the construction industry. Studies have established the relevance of construction materials in the carbon footprint of construction and the role of increasing international sourcing of these materials which emphasises the need for a multi-regional and consumption-based perspective when assessing the climate impact of construction (Hertwich, 2021; Huang et al., 2018; Onat & Kucukvar, 2020). Still, due to the aggregate nature of reporting in monetary national accounts and diverging classifications, there is little knowledge about the downstream use of construction industry supply at the macrolevel (Södersten et al., 2018). A more detailed representation of different construction subsectors (buildings, electricity infrastructure, roads, railways etc.) would contribute to a better understanding of potential future material requirements and related climate impacts and, thereby, enable assessing the macrolevel mitigation potential of subsector-specific decarbonisation strategies.

Hence, this project aims at disaggregating the construction industry by subsector in a multi-regional input-output table (MRIOT) to investigate: **How do different construction subsectors in the EU compare with regards to their input composition and related climate change impact?** This main research question requires the following sub-questions to be answered:

- What are the material inputs to different construction subsectors in the EU?
- What is the construction volume and total output of construction subsectors in the EU?
- How much does each construction subsector contribute to the carbon footprint of construction in the EU?

In answering the questions, this project adopts a quantitative modelling approach. Hence, this project uses established theories on the transfer of production activities and related emissions through our global economy to design a procedure that allows to describe the responsibility of different construction subsectors for global CO_2 emissions.

To overcome the scarcity of macrolevel data on types of construction supply, the project adopts a multi-unit approach integrating physical proxies with a monetary MRIOT to yield a detailed yet comprehensive and consistent representation of construction in the global economy. The physical proxies include material intensities for archetypical construction products from bottom-up material stock analysis (MSA) and unit processes of life cycle assessments (LCA), as well as official records of annual supply of the different building and civil engineering structures in terms of physical units (including floor area, network length, generation capacity). The model thereby combines knowledge from various core industrial ecology methods with national statistics to enhance description and scenario analysis of the environmental impacts related to our built environment.

The model is showcased on the European Union (EU) which has committed itself to carbon neutrality by 2050 (European Union, 2020) **and is about to require the collection of LCA data for buildings which may prove a valuable input for detailing the construction industry** (Energy Performance of Buildings Directive, 2024). More specifically, this study tests the usability of such physical bottom-up information for detailing the construction industry and identifies emission hot spots of the diverse construction subsectors of the EU.

The following sections provide an overview of the literature on the environmental impacts of societal-scale construction activities. Based on this review, the methodology for the proposed disaggregation procedure is derived, followed by the results for the case of the EU. An ample discussion of the results is presented in Chapter 4. The final chapter outlines avenues for future research.

1.2. Review of climate impacts of societal-scale construction activities

Despite being responsible for a relevant share in global CO_2 emissions, the global climate impact of the construction industry at the macrolevel is only assessed by few peer-reviewed articles. Estimates of the carbon footprint of construction range from 10-23% of global emissions (3.42 – 5.7 Gt CO_2 eq.) depending on the estimation method, underlying database and assessed period (Hertwich & Peters, 2009; Huang et al., 2018; International Energy Agency, 2023; Onat & Kucukvar, 2020) (cf. Appendix A). Additionally, construction and real estate services can be considered the largest economic sectors contributing to the legacy carbon footprint of manufactured capital in 2019 (Wang et al., 2023). Despite this relevant contribution to the climate crisis, few studies have highlighted the macrolevel potential for mitigating carbon emissions in the construction industry, especially outside of China, USA, UK or Australia (Gao et al., 2023; Onat & Kucukvar, 2020).

Also in the EU, construction makes a considerable contribution to the total demand-driven carbon footprint. For 2009, the EU was estimated to be one of the largest drivers of the carbon footprint of the global construction industry despite having the lowest carbon footprint intensity of all assessed regions due to its high production value (Huang et al., 2018). Construction output in the EU is projected to continue to grow by 2-3% annually in the 2020s (cf. (Oxford Economics, 2021)), and a 54% rise in annual investments in civil engineering works will be required to meet the carbon neutrality goals of the EU by 2050 (Klaaßen & Steffen, 2023). Numerous LCAs on specific buildings in Europe suggest a rising importance of embodied carbon emissions (related to construction, renovation, demolition) compared to operational energy use (Bahramian & Yetilmezsoy, 2020; Lavagna et al., 2018). Of these embodied emissions, 83-97% are indirect, partially imported, emissions, stemming from the production of material inputs rather than from the onsite assembly in high-income countries (Acquaye & Duffy, 2010; Hertwich, 2021; Huang et al., 2018; Hung et al., 2019; Onat & Kucukvar, 2020; Pomponi & Lenzen, 2017) (cf. Appendix A). Hence, a global, multi-regional footprint perspective which differentiates carbon intensities by import country is required to accurately assess the climate impact and mitigation potential of the construction industry in Europe.

1.3. Review of existing approaches to detail environmental impacts of societal-scale construction activities

To date, MRIOT-based studies have reported only aggregate results for the entire construction industry without distinguishing between structures with notably different material intensities and societal functions (Hertwich, 2021; Hertwich & Peters, 2009; Huang et al., 2018; Onat & Kucukvar, 2020; Pomponi & Stephan, 2021). This lack of differentiation is due to the underlying reporting by national statistical offices. While few national input-output tables[1] report data for construction subsectors, classifications differ and, hence, conventional MRIOT currently used for environmentally extended input-output analysis (EEIOA) contain only one aggregate construction industry (cf. GTAP (Aguiar et al., 2022), WIOD (Timmer et al., 2015), ICIO (OECD, 2023), exiobase (Merciai & Schmidt, 2018; Stadler et al., 2018), FIGARO (Cazcarro et al., 2024; European Union, 2023)) at maximum a division between civil engineering and building construction (cf. GLORIA (Lenzen et al., 2021)). This aggregate reporting impedes scenario analysis because demand for different construction subsectors may not always correlate, while supply chains of these subsectors may differ significantly (Chang et al., 2014). It also impedes accurately assessing climate change mitigation potentials by more carbon efficient provision of human needs because different societal functions and needs are represented in one industry (Vita et al., 2019).

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[1] among them eight of the 27 EU-member states: AUT, BEL, CZE, HRV, HUN, NLD, ROU, SVK, and 15 other countries: CHE, AUS, CAN, USA, BRA, CHL, COL, CPV, CRI, IDN, JPN, KOR, MEX, SEN, SGP

In contrast to EEIOA, microlevel LCA case studies can represent differences in the carbon impact by paying detailed attention to scale and kind of materials used for individual construction projects. A plethora of such LCAs on diverse individual buildings and civil engineering structures exists (for reviews see Bahramian & Yetilmezsoy, 2020; Olugbenga et al., 2019). Some authors suggest using these LCAs also for assessing the environmental impacts of building activities in larger territories (Loiseau et al., 2022; X. Yang et al., 2022). However, the case study approach of LCAs –which requires selecting materials and sources at a high level of detail that is not necessarily representative of average construction and production– does not consider material or trade balances at societal scale. Further, LCA usually requires cut-offs which makes it prone to truncation errors (Crawford et al., 2018). A recent comprehensive assessment of the differences in carbon footprints between the life cycle inventory database ecoinvent and the environmentally extended MRIOT exiobase concludes that the aggregated nature of the construction sector impeded comparison to specific products recorded in the LCA database (Steubing et al., 2022, p. 1412). Hence, further disaggregation of the construction industry in MRIOT is needed.

The disaggregation of industries, i.e. 'sector disaggregation', is a long-standing technique which has improved the usefulness of input-output tables (IOT) for environmental footprint analysis (Steen-Olsen et al., 2014; Wenz et al., 2015; Wood et al., 2014). For instance, exiobase relies on the disaggregation of the environmentally relevant energy and agricultural sectors (Stadler et al., 2018). More detail is also achieved in the physical Food and Agricultural Biomass Input-Output Model (FABIO) which has aided a surge in the environmental impact analysis of diets and food systems (Bruckner et al., 2019). Sectoral disaggregation has also sporadically been applied to the construction industry, in the national IOTs of Ireland (Acquaye & Duffy, 2010), Sweden (Nässén et al., 2007), Australia (Yu et al., 2017) and China (Chang et al., 2014, 2016; Zhang & Wang, 2016). The results highlight the importance of civil engineering structures compared to buildings in terms of carbon footprint and intensity, as well as differences in the energy intensity of urban and rural buildings. Other disaggregation efforts in the construction domain have focussed on material inputs of construction rather than types of construction supply (cf. Crawford et al., 2022; Dixit, 2017). Overall, a multi-regional perspective on the carbon footprints of different construction subsectors is missing. In particular, the use of physical bottom-up estimates for disaggregating the construction industry in a MRIOT remains unexplored.

Hybrid MRIOT models are promised to be more accurate than purely monetary IOT or process-based LCAs by avoiding the upstream truncation error while retaining sectoral detail (for a discussion see Pomponi & Lenzen, 2017; Schaubroeck, 2019; Y. Yang & Heijungs, 2019). Examples of hybrid LCA-EEIOA in the construction industry have mostly focussed on individual buildings (cf. Dixit & Singh, 2018; Zhang et al., 2020), but Chang et al. (2014) use a similar framework for disaggregating construction in the Chinese IOT. Additionally, multi-unit MRIOT expressed in physical units except for services are also useful for practitioners when modelling demand scenarios and scenarios of a circular economy as it avoids conversion of available units with prices (Aguilar-Hernandez et al., 2018; Merciai & Schmidt, 2018; Towa et al., 2022).

2. Methods & Data

2.1. EEIOA terminology

Environmentally extended input-output analysis (EEIOA) is a method used to understand the societal-scale environmental impacts of industries and countries (Miller & Blair, 2009). Particularly, it allows considering the role of trade in mediating environmental impacts and assessing consumption-based rather than just the territorial environmental impacts of countries. To do so, EEIOA combines international and interindustry trade (**Z**) and consumption data (**Y**) with environmental extensions (**F**). The trade data is harmonised in a square matrix, **Z**, that contains information on the source, i.e. the production technology (columns of **Z**), and destination (rows of **Z**) of each industry's supply. For instance, **Z** specifies how much the 'construction' industry of country A in one year spent on, i.e. used, inputs from the 'fabricated metal products' industry in country B to produce its annual supply. Conversely, it also describes which other industries the construction industry supplied to, e.g., how much the 'education' sector spent on 'construction' activities for the maintenance of educational buildings.

Most supply of the construction industry, however, is creating durable goods and recorded as gross fixed capital formation in the final demand matrix, **Y**. The sum of intermediate and final demand for an industry's supply forms the total output vector, **x**. The upstream requirements for inputs can be linked to environmental pressures –in this study exemplified by CO_2 emissions– using a vector that records direct environmental pressure per total output for each subsector in each country[2], $\mathbf{f} = \mathbf{F}\hat{\mathbf{x}}^{-1}$, and using the Leontief inverse formula: $\mathbf{m} = \mathbf{f}(\mathbf{I} - \mathbf{A})^{-1}$ where **I** is an identity matrix of the shape of **Z** and where **A**, also called the technical coefficients or direct requirement, is the share of each industry input in total output per sector, $\mathbf{A} = \mathbf{Z}\hat{\mathbf{x}}^{-1}$, so that the multiplier **m** represents the environmental footprint caused directly and indirectly upstream by one unit of final demand for products finally produced by each industry in each country.

Hence, the total environmental footprint of final demand for an industry is: $\mathbf{e} = \mathbf{m}\hat{\mathbf{y}}$, where **y** is the sum across consuming countries and actors of **Y**, $\mathbf{y}_m = \mathbf{Y}_{m \times n}\mathbf{1}_n$. The location of environmental impacts that are related to the environmental footprint can be revealed using $\mathbf{E} = \hat{\mathbf{f}}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{y}}$. The contribution of direct inputs of an industry to the

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[2] In line with common practice, the annotation uses italic non-bold letters for scalars, bold non-capital letters for vectors, and bold-capital letters for matrices. The subscript on scalars indicates indices. The subscript on matrices and vectors indicates the shape where m is the number of rows and n the number of columns. ^ indicates a diagonalised vector. ' indicates a transpose. := indicates that the variable is reassigned the result of the term.

environmental multiplier of that industry can be represented by the Hadamard product, $\mathbf{C} = \mathbf{A} \odot \mathbf{M}$, where $\mathbf{M}$ is a matrix of the shape of $\mathbf{A}$ that contains $\mathbf{m}$ in each row, so that $\mathbf{1}'_m \mathbf{C}_{m\times n} + \mathbf{F}_{1\times n} = \mathbf{m}_n$.

2.2. Overview of the disaggregation procedure using physical proxies

The critical addition of this study is to propose a procedure for using physical bottom-up data to disaggregate construction inputs in the monetary base MRIOT, i.e. to differentiate the production technology of construction subsectors (Figure 1). Physical estimates encompass any data given in mass, energy, or spatial units such as material intensities, floor area, network length or energy generation capacity. To achieve this combination, the procedure uses material prices and top-down accounts of production value and value added per detailed subsector to balance the bottom-up estimates with the top-down accounts.

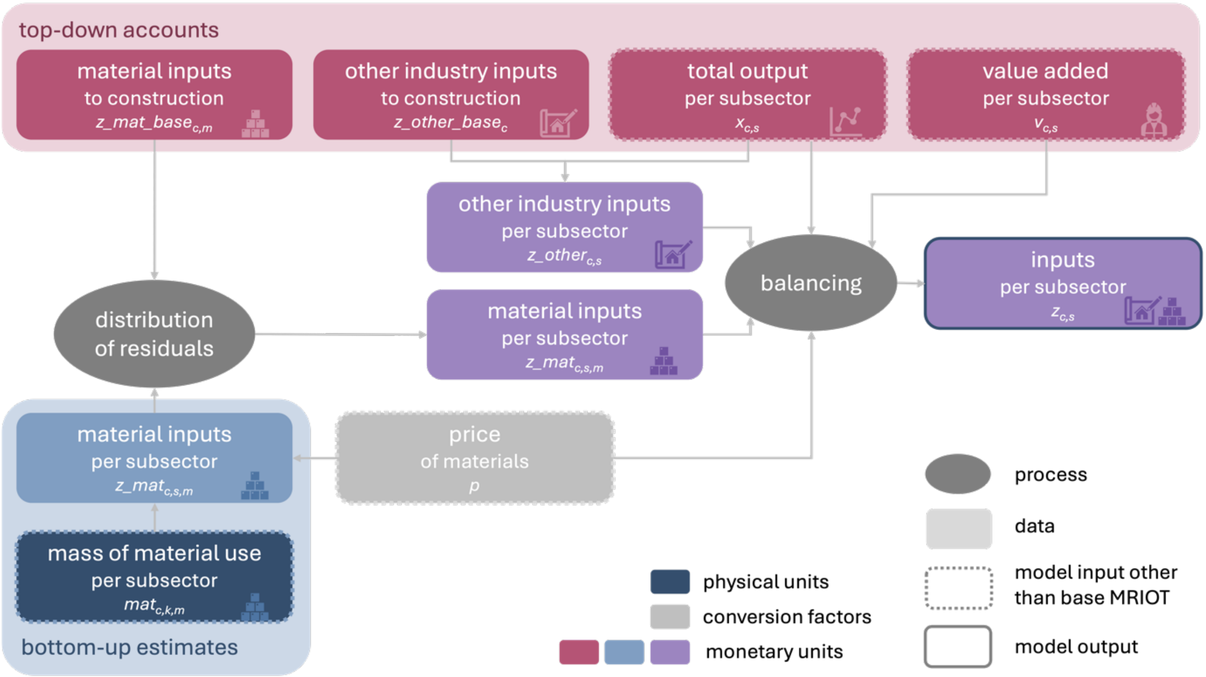

Fig. 1: Overview of the disaggregation of the inputs to construction using physical bottom-up estimates of material use.

The procedure entails, first, the calculation of the total mass (*mat*) **of each material** (*k*) used for construction by each subsector (*s*) of each country (*c*) by multiplying material intensities (*mi*) in mass units with physical construction volumes (*x_physical*) per structure (*t*) and country, where T_s is the set of structures that form part of each subsector:

$$mat_{c,s,k} = \sum_{t\in T_s} mi_{c,t,k} * x\_physical_{c,t,k} \qquad (1)$$

Physical construction volumes are derived from building permit data as well as annual changes in stocks of civil engineering structures in combination with lifetimes which enable accounting for structure replacements that are hidden in annual stock changes. Material intensities are derived from material content (in mass units) per unit of structure (in square metres of floor area, kilometres of network length, megawatt of energy generation capacity). These material content estimates are adjusted using residual percentages to account for extra material that is purchased as construction input but is not incorporated into the final structure, e.g., broken glass. The estimates are further adjusted using recycling percentages to account for material that becomes part of the structure but does not need to be bought by the construction company as additional input because it can be reused from onsite available materials, e.g., gravel in road construction.

The total mass of materials used for construction in each subsector is then converted to monetary units using material prices (*p_initial*)**, and the value of the inputs** (*z_mat*) **per material is aggregated by material input sectors** (*m*) where K_m is the set of materials that form part of each material input sector (cf. Appendix Table D1):

$$z\_mat_{c,s,m} = \sum_{k \in K_m} p\_initial_{c,k} * mat_{c,s,k} \qquad (2)$$

The prices are material- and use-country- but not source-country-specific. This assumes homogenous prices across supplying countries of each material. However, since the model also assumes a homogenous sourcing structure of each material across subsectors, and most of the direct material inputs to construction such as aggregates, wood, fabricated metal products (including steel bars and window frames) and non-metallic mineral products (including bricks, stone and cement) are primarily domestically sourced (cf. Appendix Figure D1), this assumption is acceptable.

For any subsector for which insufficient information on material intensity or physical construction volume is available (in this study: ‘other civil engineering’), technical coefficients (*a*) of the aggregate construction sector as recorded in the base MRIOT are assumed in a first step and scaled to the monetary total output recorded in official statistics:

$$z_{mat_{c,s,m}} = a_{c,m} * x_{c,s} \qquad (3)$$
$$\text{for } s\text{: Other civil engineering}$$

This assumes that this subsector does not differ from ‘average’ construction in the respective country.

Next, residuals of inputs to construction are calculated and distributed across subsectors. Residuals (*r*) comprise any deviations of the bottom-up estimates of material inputs (*z_mat*) to construction across subsectors of a country from the material inputs to construction of that country recorded in the base MRIOT (*z_mat_base*):

$$r_{c,m} = z\_mat\_base_{c,m} - \sum_{s \in S} z\_mat_{c,s,m} \tag{4}$$

Potential sources of these deviations are manifold including inaccuracies in material prices, material intensities, physical construction volumes, residual percentages, recycling percentages, delays in construction or also the assumption that the production technology of 'other civil engineering' is equal to average construction. The residuals may take positive (in case of underestimations) or negative value (in case of overestimations). Hence, these residuals are distributed by the following procedure: Any negative residuals that can be directly deducted from 'other civil engineering' without causing negative inputs, are deducted:

$$z\_mat_{c,s,m} := z\_mat_{c,s,m} + r_{c,m} \tag{5}$$
$$\text{for } s\text{: Other civil engineering}$$
$$\text{where } r_{c,m} < 0 \text{ and where } z\_mat_{c,s,m} + r_{c,m} > 0$$

This assumes that these minor negative residuals are present because of an actually lower than average material use by 'other civil engineering'. All other residuals are distributed across subsectors according to the subsector share in total output (*x*) while ensuring that input values stay positive or zero:

$$z\_mat_{c,s,m} \coloneqq z\_mat_{c,s,m} + r_{c,s,m} \tag{6}$$
$$\text{for } r_{c,s,m} = r_{c,m} * \frac{x_{c,s}}{\sum_{s \in S} x_{c,s}}$$
$$\text{where } z_{mat_{c,s,m}} + r_{c,m} > 0$$

This assumes that these larger residuals are present because of some inaccuracies in the bottom-up procedure. The impact of this redistribution procedure on the production technology of different subsectors is displayed in Appendix Figure E1.

Supply of construction to intermediate (*z*) and final demand (*y*) per user (*d*) as recorded in the base MRIOT is disaggregated into supply of each subsector using subsector shares of total output derived from official statistics:

$$z_{c,d,s} = z\_base_{c,d} * \frac{x_{c,s}}{\sum_{s \in S} x_{c,s}} \tag{7}$$
$$y_{c,d,s} = y\_base_{c,d} * \frac{x_{c,s}}{\sum_{s \in S} x_{c,s}} \tag{8}$$

This is an established procedure in the purely monetary disaggregation of the construction sector (Chang et al. 2014; R. Sinha, R. Wood, L. Rousseau, personal communication, November 9, 2023). Consequently, homogenous shares across supply to different industries are assumed. For instance, if the educational sector of country A spent 100,000$ on construction activities for maintenance purposes and the share of railway construction in country A's total output of construction is 10%, the procedure assumes that the educational sector spent 10,000$ on the maintenance of railways – even though it is likely that the sector spent all on maintenance of educational buildings rather than transport infrastructure. A variant of this assumption where some intermediate demanding industries are matched with construction subsectors based on common sense, e.g. intermediate demand for construction by the electricity industry with the construction of electricity infrastructure, is presented as part of the sensitivity analysis (cf. Appendix Figure F7).

Given official statistics on total output and value added of each construction subsector, the production technology of each subsector is rebalanced to ensure that total inputs equal total output. The rebalancing entails adjustments to the material prices (*p*) as well as the size of inputs which were not calculated using the physical bottom-up procedure (*z_other*). These inputs, consequently referred to as 'other industry inputs', include services, energy, and machinery. First, a split of the 'other industry inputs' recorded in the base MRIOT (*z_other_base*), as well as the environmental extensions (*f_base*), between subsectors in line with the subsector's share in total output of construction is performed assuming that each construction subsector uses the same amount of other industry inputs and direct environmental pressures per unit of supply:

$$z\_other_{c,s} = z\_other\_base_c * \frac{x_{c,s}}{\sum_{s \in S} x_{c,s}} \tag{9}$$

$$f_{c,s} = f\_base_c * \frac{x_{c,s}}{\sum_{s \in S} x_{c,s}} \tag{10}$$

As a result, total inputs (including material inputs, other industry inputs, and value added) exceed the total output in cases where the physical bottom-up procedure allocated more material inputs to one subsector over another, or where the official statistic indicates a higher value added (*v*) for one sector over another. Hence, assuming that information on value added and physical material inputs is correct, it is reasonable to assume that other industry inputs differ between subsectors, e.g. that electricity infrastructure construction spends relatively more on materials over services per unit of supply than other subsectors, and that the material prices are not fully accurate, e.g. that the price of the average supply of the rubber and plastics industry does not match exactly those plastic products used by the different construction subsectors. The exact distribution of other industry inputs across subsectors, as well as adjusted material prices for each subsector, is found by aiming for eliminating the distance of total inputs from total outputs while minimising the deviation of other industry inputs (*z*) and material prices (*p*) from initial values (*z_initial, p_initial*) per country (*C*), subsector (*S*) and material (*M*), and maintaining the overall balance of inputs (*z_other*: other industry inputs, *p*mat*: material inputs, *v*: value added) to construction per country:

$$\min_{p, z\_other} \sum_{c,s,m \in C,S,M} \left(1 - \frac{z\_other_{c,s}}{z\_other\_initial_{c,s}}\right)^2 + \left(1 - \frac{p_{c,s,m}}{p\_initial_{c,s,m}}\right)^2 * 5 \tag{11}$$

subject to

$$\sum_{m \in M} p_{c,s,m} * mat_{c,s,m} + z\_other_{c,s} + v_{c,s} = x_{c,s}$$

$$\sum_{s \in S} z\_other_{c,s} = \sum_{s \in S} z\_other\_initial_{c,s}$$

$$\sum_{s \in S} p_{c,s,m} * mat_{c,s,m} = \sum_{s \in S} p\_initial_{c,s,m} * mat_{c,s,m}$$

The deviation of prices is weighted five times higher than a deviation of other industry inputs to account for higher reliability of the price estimates. The optimisation problem is implemented in pyomo and solved using the Interior Point Optimizer (ipopt) (Bynum et al., 2021; Wächter & Biegler, 2006).

2.3. Scope of the case study

The procedure is showcased for one year for the construction sector of each **EU-27 member state** (European Union, 2024). The scope of the case study is mainly driven by data availability. **2018** was chosen as target year since this is the latest year with the highest availability of data on physical construction volumes (cf. Appendix Figure C1).
The case study disaggregates the construction sector into 18 structures that are part of **five broader subsectors** (Table 1). Each of these subsectors entails both construction of new structures and construction activity for the maintenance and gradual replacement of structures. Electricity infrastructure also entails related grid infrastructure. The subsectors are oriented along common construction subsector classifications such as the UN Central Product Classification (UN Statistics Division, 2023) and EU NACE (Eurostat, 2008). However, the disaggregation pursues a purely horizontal division of subsectors, i.e. between different kinds of structures such as buildings and roads, rather than vertical division, i.e. between different construction activities such as digging and roofing. Hence, 'Specialised construction activities' are allocated to the Construction of Buildings, Roads, Railways, Electricity Infrastructure, and Other Civil Engineering Projects proportional to the respective share in total output.

Table 1: Construction subsectors and related structures according to the horizontal division applied in this study (cf. Appendix Table C1).

Subsectors	Structures
Construction of Buildings	Buildings, dwelling multi
	Buildings, dwelling single
	Buildings, offices
	Buildings, educational
	Buildings, trade

	Buildings, other
Construction of Roads	Roads, motorway
	Roads, state
	Roads, provincial
	Roads, communal
Construction of Railways	Railways
Construction of Electricity infrastructure	Electricity infrastructure, combustible fuels
	Electricity infrastructure, hydro
	Electricity infrastructure, nuclear and other fuels
	Electricity infrastructure, wind
	Electricity infrastructure, solar photovoltaic
	Electricity infrastructure, other renewables
Construction of Other Civil Engineering	Other civil engineering

As construction materials have the largest impact on the carbon footprint of construction (cf. Appendix Figure F1; Huang et al., 2018; Onat & Kucukvar, 2020), the six **input sectors** and their corresponding materials as presented in Table 2 are disaggregated using the physical bottom-up procedure.

Table 2: Key material input sectors with corresponding materials for which data in physical units was collected (cf. Appendix Table D1).

ICIO sector	Material
Mining and quarrying, non-energy producing products	Sand and clay
Wood and products of wood and cork	Timber
Basic metals	Aluminium
	Copper
	Lead
	Other metals
Fabricated metal products	Steel
	Aluminium
	Copper
	Lead
	Other metals
Other non-metallic mineral products	Concrete
	Asphalt concrete
	Mortar
	Bricks
	Stone
	Glass
Rubber and plastics products	Plastics

2.4. Data sources and preparation for the case study

The disaggregation of the construction sector is performed in the 2021 version of the existing MRIOT Inter-Country Input-Output (ICIO) (OECD, 2023). The 2021 version is chosen over the latest version since the more recent update does not contain environmental extensions. The environmental extension used in this study comprises carbon dioxide (CO_2) emissions. ICIO is chosen over the more environmentally disaggregated exiobase since ICIO has more recent complete updates (Stadler et al., 2018; Wood et al., 2014). Further, ICIO is preferred over the EU-specific MRIOT FIGARO (European Union, 2023) to ease replication of the procedure for other world regions.

Three approaches for calculating the carbon multipliers and related carbon footprint of the disaggregated MRIOT are compared. First, an endogenous approach using the multiplier composition, **C**, given by the broad material input sectors of the ICIO database. Secondly, a finer representation of specific materials that form part of each material input sector in ICIO as suggested by the bottom-up estimates is considered. For this *material-specific approach*, those parts of the multiplier composition that refer to material inputs are calculated using the carbon intensity of materials as specified in the detailed FIGAROe3 database (Cazcarro et al., 2024). The third *physical material-specific approach* applies the same level of detail but in physical units by calculating parts of the multiplier composition using the carbon intensity of material per kilogram specified in the physical BONSAI database (BONSAI, 2024).

Details of the specific data used for the disaggregation are described in Appendix B. Country-specific total output shares and value added is derived from the EU Structural Business Statistics (Eurostat, 2024a). For the bottom-up estimate, physical construction volumes per country are calculated based on various official records of the EU Statistical Office Eurostat (EU Directorate-General for Energy, 2024; Eurostat, 2024b, 2024c, 2024d; Nguyen et al., 2023) and material content intensities are derived from MSA and LCA reviews (Deetman et al., 2020, 2021; Marinova et al., 2020; Röck, 2023; Wiedenhofer et al., 2024). Use-country specific basic prices of materials are taken from the multi-unit BONSAI database available for 2016 (BONSAI, 2024).

To allow further development beyond the scope of this study, the accompanying code is designed to be adaptable to diverse data inputs with the necessary technical requirements described in Appendix B.

3. Results

The disaggregation using the physical bottom-up estimates affects the conclusions about construction sector climate impacts in three notable ways: 1) the total size of the carbon footprint of construction, 2) the carbon intensity of different construction subsectors, and 3) the location of emissions related to each subsector. Each of these aspects is elaborated below.

3.1. Difference in total carbon footprint of construction

The carbon footprint of construction, i.e., the sum of the direct and indirect CO_2 emissions incurred by final demand for construction activities, is significantly larger when considering a higher resolution of material inputs than specified in the base MRIOT (Figure 2). Linking specific demand for materials of EU construction as indicated by the disaggregated MRIOT to material-specific multipliers given by the FIGAROe3 database (Cazcarro et al., 2024) suggests a 24% larger carbon footprint of construction than indicated by the original ICIO database. When connecting the material inputs in physical units to the multipliers of the multi-unit BONSAI database (BONSAI, 2024), the carbon footprint is even more than two times larger than in the base case. This divergence results from the tendency of the specific materials used for construction (especially concrete, cement, steel, aluminium) to have a relatively higher carbon intensity than the broad sectors available in ICIO which the materials are part of (cf. Appendix Figure F3). For instance, the carbon multiplier of the dominant construction material concrete is 59% higher in FIGAROe3 and almost four times higher BONSAI than their counterpart ICIO sector 'other non-metallic mineral products'.

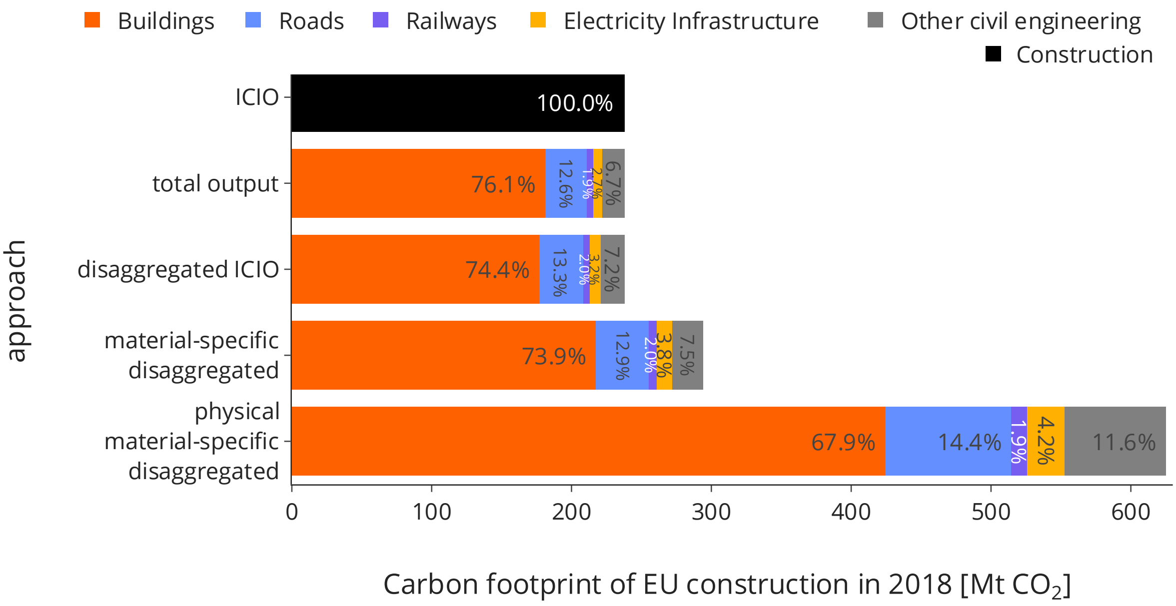

Fig. 2: Carbon footprint of EU-27 construction in 2018 by subsector and disaggregation approach.

This highlights the relevance of granularity in national and environmental accounts for understanding the environmental impacts of our built environment. Different from an approach purely based on monetary trade statistics that are reported in broad sector classifications, the use of material-specific physical proxies in this study enables this granularity.

3.2. Subsector composition of the carbon footprint of construction

In terms of composition, the disaggregated production technology of construction suggests a higher carbon intensity of civil engineering compared to building construction. Across approaches, buildings bear the majority of the carbon footprint of construction in the EU and in all member states (except Greece) in line with being the subsector with the largest production value (Figure 2, Appendix Figure F9). Nevertheless, by representing differences in production technology using physical proxies, civil engineering sectors, in particular electricity infrastructure and other civil engineering – including structures such as water and non-electric fuel infrastructure–, tend to be more carbon intensive among EU-27 member states than building construction (Figure 3). These differences in carbon intensity are highly relevant for scenario analysis and investment decisions since without disaggregation one would –in an extreme case such as hydropower-dominated Austria– underestimate the consequences of an investment in electricity infrastructure on embodied emissions by 101%.

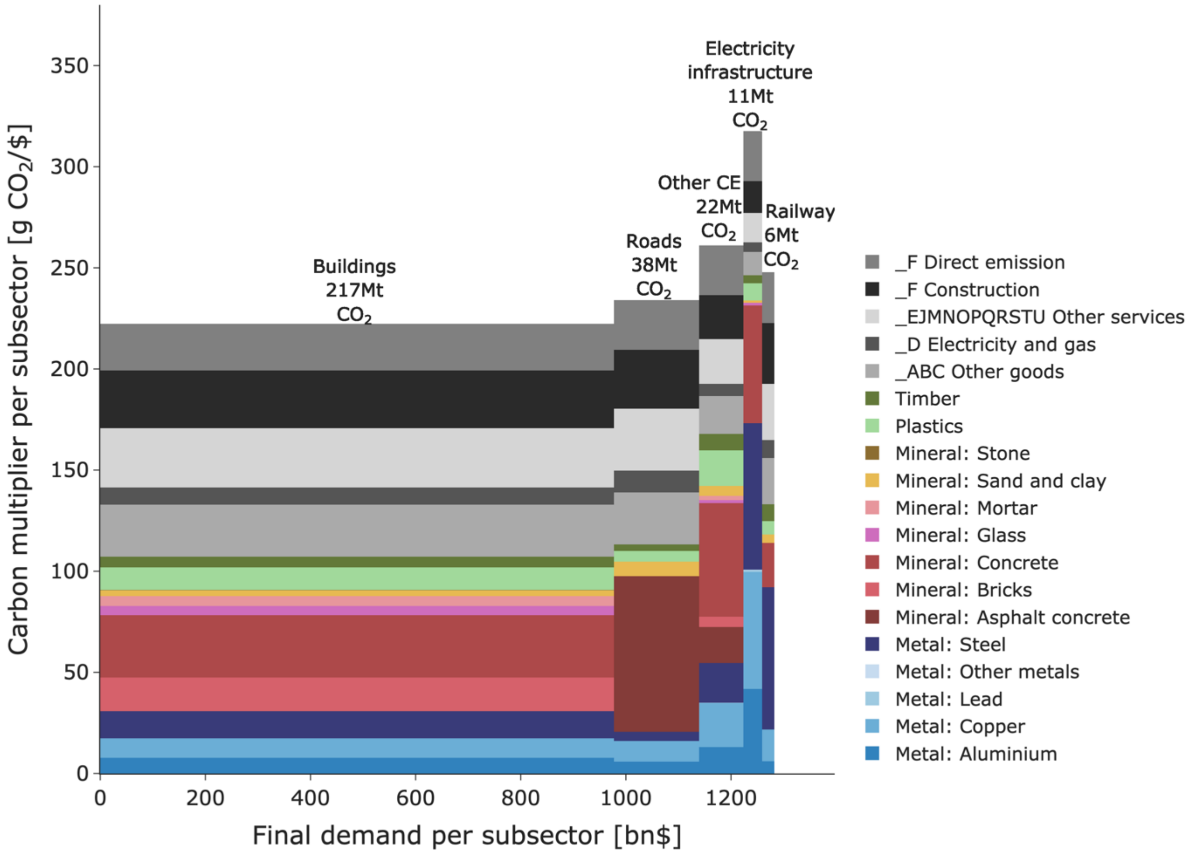

Fig. 3: Composition and size of the carbon footprint of construction subsectors in the EU-27 in 2018. Carbon footprint (area) based on carbon multiplier and its input composition (height) and final demand and its subsector composition (width). Other CE: Other civil engineering. Based on the material-specific approach. The carbon multipliers represent the direct and upstream CO_2 emissions incurred by spending one dollar on construction subsectors.

The higher carbon intensity translates into a larger share of civil engineering in the carbon footprint of construction than its share in total output (Figure 2). The difference becomes especially apparent when applying material-specific and physical multipliers. For instance, while the construction of electricity infrastructure makes only 2.7% of the supply of construction in monetary units, 3.2% of construction-related emissions are attributed to electricity infrastructure construction using only ICIO multipliers, and 3.8% and 4.2% using FIGAROe3 and BONSAI multipliers for material inputs, respectively. For road construction, the carbon intensity relative to the other subsectors is more ambiguous and depends on the material multipliers applied. Using ICIO and BONSAI material multipliers, road construction is significantly more carbon intensive than building construction, whereas using the FIGARO material multipliers as depicted in Figure 3 it is only 5% more carbon intensive than building construction due to the higher carbon multiplier for bricks and the lower multiplier of concrete (cf. Appendix Figure F3).

3.3. Sourcing composition of carbon footprint by subsector

Next to carbon intensity, the disaggregation in a multi-regional IOT allows understanding where emissions take place that are related to each subsector. This sourcing composition suggests that electricity infrastructure and railway construction potentially relies more on outsourced (non-domestic) CO_2 emissions than other subsectors. Throughout the EU, only 43% of the carbon footprint of electricity infrastructure is emitted in the country where the infrastructure is built, while for building and road construction and other civil engineering it is 48-52% (Figure 4). This difference can be explained by the higher share of basic metals such as aluminium and copper in electricity and railway infrastructure which are subject to more foreign sourcing (Appendix Figure D1) and have a high carbon intensity (Appendix Figure F3).

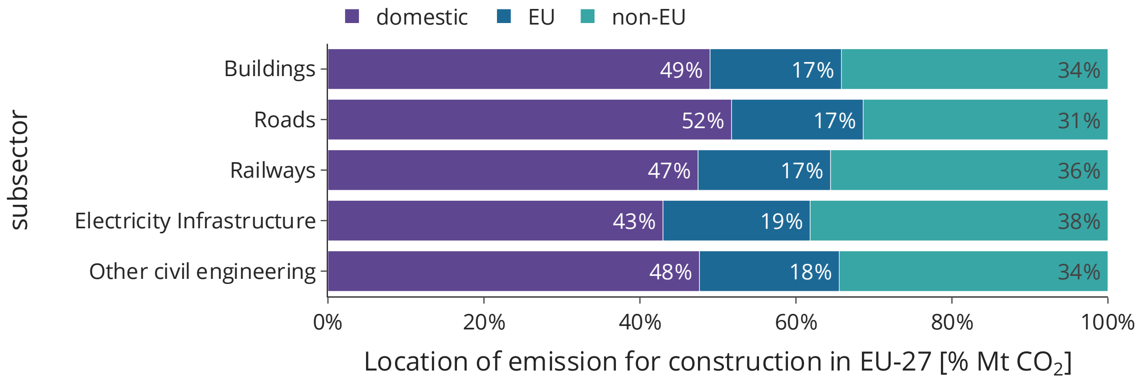

Fig. 4: Distribution of the carbon footprint of EU construction subsectors across emission source. Domestic: the country of construction; EU: any other EU-27 member state; non-EU: any other country. Based on the endogenous disaggregated ICIO approach.

3.4. Drivers of subsector differences in carbon intensity and sourcing

Potential reasons for differences in carbon intensity and location of emissions of subsectors as represented by the disaggregation of production technology are

manifold including the specific share of value added vs. industry inputs in the unit cost, the composition of industry inputs and the specific carbon intensity of these industry inputs (cf. Appendix Figure F4). The contribution of each of these factors is elaborated below.

Rather than the differences in value added intensity, the composition of the industry inputs defines the carbon intensity of subsectors at the EU level. The composition of the unit cost of construction subsectors in the EU seems to suggest that the share of value added in the unit cost of construction positively correlates with the carbon intensity (Appendix Figure E1). Building, road and railway construction have a low value-added intensity per unit of supply as well as a lower carbon intensity; whereas electricity infrastructure and other civil engineering both have a high value-added intensity and a high carbon intensity. Nevertheless, this apparent correlation does not indicate causation. In fact, ceteris paribus given the same composition of industry inputs, a higher share of value added in the unit cost –i.e. spending more of the subsector revenue on labour, capital and taxes– would mean less value is spent on industry inputs which would translate into a lower carbon intensity per unit of subsector supply. Also, a comparison of value-added intensity against the carbon intensity of all 135 country-subsector combinations detailed in this study supports this negative correlation (Appendix Figure F4).

In terms of industry inputs, especially metals and other non-metallic mineral inputs appear to explain the variation in carbon intensity (cf. Appendix Figure F4**).** At the EU-level this is illustrated by the higher metal intensity of electricity, railway infrastructure and other civil engineering as well as the high mineral intensity of road construction and other civil engineering which translates into a higher carbon intensity per investment than building construction.

Here, the **material-specific approach leverages the possibilities of a disaggregation using physical proxies by allowing to identify which materials and inputs in particular are responsible for emissions of each construction subsector** (Figure 3). For example, more than half of the CO_2 emissions per unit of final demand for electricity infrastructure in the EU is related to metals including steel, aluminium and copper, whereas emissions related to bricks and glass are only notable in building construction. Different from average construction activity, road construction requires very few metal inputs per unit of supply which translates to a low share in the carbon multiplier. Inputs such as aggregates and stone, on the other hand, have only a very low influence on the carbon footprint of construction regardless of the subsector despite their high share in mass (Appendix Table D3) and moderate share in value (Appendix Figure E1). **These trends are also visible at a per-country level although with more variance** as a result of the country-specific structure composition of subsectors and material intensities represented in the physical proxies, as well as in the monetary model inputs such as the production technology of the aggregate construction sector, the share of value added in the total output, and sourcing-dependent differences in the carbon intensity of construction materials (Appendix F5).

The share of 'other industry inputs' including services, energy, and machinery inputs only negatively correlates with the carbon intensity when applying BONSAI carbon multipliers for materials (cf. Appendix Figure F4), i.e. when increasing the carbon intensity of materials relative to other industry inputs (cf. Appendix Figure F3). While most other industry inputs have a lower carbon intensity than material inputs, electricity generation – which is included in the 'other industry inputs' – has a comparably high carbon intensity which outweighs several material inputs. It needs to be highlighted that these other industry input intensities result from balancing. For instance, given a large value-added intensity of electricity infrastructure recorded in the official statistics in combination with a relatively large share of direct material inputs in the unit cost estimated using the physical bottom-up procedure, services, energy and machinery inputs have only been allocated 21% of the unit cost of EU electricity infrastructure construction, whereas these inputs make 46% of the unit cost of building construction. This assumes that compared to an investment into buildings, a higher share of the value is spent on carbon-intensive material production than on rather carbon-efficient other industry inputs per investment in electricity infrastructure projects.

4. Discussion & Limitations

As presented in the previous chapter, the consideration of physical bottom-up estimates to detail the built environment in monetary input-output models enables a more attuned representation of the diverse trade relations of construction subsectors and their climate implications. These results are broadly in line with previous studies on a more detailed representation of the construction industry. Still, the results for the specific case should be taken with some caution since the underlying data is subject to a number of limitations and inaccuracies which are outlined below. Various challenges need to be addressed for a robust integration of data on physical processes in the built environment and monetary input-output tables.

4.1. Comparison of disaggregation results to other studies

Despite inaccuracies, the basic conclusions concerning carbon intensity and the distribution of the carbon footprint align with other studies that perform a disaggregation of the construction industry using different procedures.

The finding that civil engineering, in particular electricity infrastructure construction and other civil engineering, is more carbon intensive than building construction aligns with findings on the Swedish, Australian, Chinese, and Global construction sector. An early disaggregation of the Swedish IOT in 2000 finds a 30% higher carbon intensity of civil engineering than building construction (Nässén et al., 2007). Similarly, Yu et al. (2017) find that heavy civil engineering (including electricity infrastructure, railways and other civil engineering) had the largest carbon multiplier with 420g CO_2 per dollar compared to road and building construction in the Australian construction sector in 2013. Different from this study, heavy civil engineering is found to be responsible for almost half (47%) of the carbon footprint (Yu et al., 2017). However, this discrepancy may be explained by different investment priorities in Australia at that time compared to in the EU in 2018, as well as by a potentially lower carbon intensity of building construction due to a higher share of wood-frame construction. For instance, Sinha et al. (under review) –who disaggregate the construction industry based on monetary proxies derived from detailed national IOTs– show that the share of residential building construction in the carbon footprint of construction is considerably larger if assuming Canadian production technology rather than US or Japanese production technology. Also, Sinha et al. (under revision) suggest that construction of utility infrastructure (including electricity and water infrastructure) and other construction has a larger carbon multiplier (450-690g CO_2eq. per dollar) than transport infrastructure (300-350g) and building construction (280-300g) in Europe when assuming US or Japanese production technology for the construction subsectors in line with this study. Similarly, Chang et al. (2014) –which focusses on detailing the building sector in China with civil engineering acting as a residual sector– finds a considerably larger energy intensity of civil engineering than different types of building construction.

The critical addition of this study to the disaggregations of the national IOT (Chang et al., 2014; Nässén et al., 2007; Yu et al., 2017) is to detail the civil engineering sector by clearly differentiating electricity infrastructure and two types of transport infrastructure (roads and railways) which have notably different production technology. The disaggregation in a multi-regional IOT further offers the benefit of understanding potential trade shifts related to shifts of investments between different structures (cf. Section 3.3). The author is not aware of any study which has pursued a similar analysis. Moreover, the integration of bottom-up estimates in this study adds to the monetary approach by Sinha et al. (under revision) by proposing a mechanism that allows composing country-specific production technology for construction subsectors rather than assuming production technologies similar to those of the few countries with very detailed national IOT such as the USA, Canada or Japan. This also allows to clearly identify the specific inputs that contribute to differences in carbon intensity between structures and, hence, to reveal differences in the total size of the carbon footprint given a higher input resolution. The tendency of the carbon footprint of construction to increase with input resolution aligns with a MRIOT comparison by Onat and Kucukvar (2020) which suggests that the carbon footprint of construction is higher in the more detailed databases EORA (Lenzen et al., 2012) and exiobase (Stadler et al., 2018) compared to the more aggregated World Input-Output Database (Timmer et al., 2015).

4.2. Uncertainty and ambiguity in central model inputs

The combination of datasets revealed significant discrepancies between top-down accounts and bottom-up estimates of material use in construction which show as residuals. Across EU member states, metal and wood contents appear underestimated. Bottom-up estimates converted to monetary units only represent 16% of the basic metals and 34% of the wood products recorded as inputs to construction in the base MRIOT. Also, estimates of rubber and plastic products (58%), other non-metallic minerals (67%) and fabricated metal products (82%) are lower at the EU level although overestimated in individual countries.

A comparison with industry figures suggests that inaccuracies in the physical estimates are the cause of the underestimation more than material prices. For several key materials, the initial estimates of the total mass of material used in four main construction subsectors (buildings, roads, railway, electricity infrastructure) in the EU-27 are considerably lower than industry figures on total material supply to construction (Appendix Table D3). For steel, glass and timber, total production volumes of the specific types of materials used for construction reported by industry associations (Delahaye et al., 2023; EOS, 2023; Eurofer, 2023; FAO, 2024; Glass for Europe, 2024) tend to be roughly three times larger than the amount of material estimated in this study. The estimates for concrete use by the four construction subsectors in the EU also appear at least one third lower compared to industry figures (Cembureau, 2016, 2023). However, the use of asphalt concrete seems to align with EAPA (2024). Also, in comparison with the Dutch physical IOT (Delahaye et al., 2023), the use of concrete and asphalt concrete, as well as stone and copper, in Dutch construction estimated in this study are within a 20% range. It is implausible that all these materials that are not yet accounted for by the total material inputs to building, road, rail and electricity infrastructure construction are supplied to 'other civil engineering' activities which mainly comprise pipeline, greenhouse, port, and waterway construction.

Potential reasons for this apparent underestimation of physical material supplied to the construction industry include inaccurate estimates of stocks, lifetimes, material content, residual percentages, or recycling percentages. For instance, map- and satellite-imagery based estimates of road and rail infrastructure (van Engelenburg et al., 2024; Wiedenhofer et al., 2024) are considerably higher than official records of road and rail infrastructure which are used here due to their temporal coverage (Eurostat, 2024e; Nguyen et al., 2023). Scaling the official stock estimates according to Wiedenhofer et al. (2024) would even exceed the supply reported by the European Asphalt Pavement Association by a third (Appendix Table D3). At the same time, this would translate to a higher share of road construction in the carbon footprint of EU construction of 14.8% (compared to 13.3% in the default) and to a significantly larger carbon intensity of spending on road construction (Appendix Figure F7).

Secondly, the stock-driven estimation of construction volumes of roads, railways and electricity infrastructure requires assuming lifetimes for these types of structures.

Whereas for roads and railways material-specific lifetimes are available, for electricity infrastructure lifetimes had to be assumed based on a small sample of studies. As lifetimes are socially dependent, e.g. lifetime can be shortened by political and investment decisions (Thomsen & Van Der Flier, 2011), such case-based lifetimes are subject to uncertainty at societal scale. Hence, strong deviations of a subsector carbon multiplier from aggregate construction (such as road construction in Cyprus, railway construction in Finland or electricity infrastructure construction in Luxemburg) may not only be attributed to differences in production technology but also result from the assumption that stocks are continuously maintained and replaced.

A similar issue of small sample sizes applies to material content estimates. There is little interest to report material content in structures without legislation, and research has focussed on quantifying material content of residential buildings (Deetman et al., 2020). Hence, only a relatively small number of studies exists, which makes average material content estimates prone to outliers and does not allow for country-level nor temporal differentiation. While it can be assumed that material composition of civil engineering structures is rather similar across countries and time since functionality and cost-effectiveness is the primary concern in such structures, the choice of materials in buildings is more subject to location- and time-dependent identity-building, cultural expression and climatic differences (Sadalla & Sheets, 1993). The present study aimed to circumvent this by combining material content estimates from various reviews to enable differentiating between climate zones and by applying medians instead of means. Fishman et al. (2024) circumvent this lack of data by imputing missing data for various world regions based on a machine learning algorithm, and by specifying ranges of material intensities rather than averages. Still, applying the range of material intensities specified in Fishman et al. (2024) only reduces the gap for steel, bricks, and timber, while for all other estimates it only reaches the default estimates used in this study if applying the 75th percentile material content estimates (cf. Appendix Table D3).

Additionally, the material contained in a structure does not equal the material that is needed to construct the structure for two reasons: distribution and assembly losses, and onsite recycling. The procedure suggested here takes this into account by applying residual and recycling percentages based on available literature and expert opinion (cf. Appendix B). However, similar to the lifetimes, there are no canonical assumptions on society-wide average residual or recycling percentages. Hence, there may be considerable error in the assumed residual and recycling percentages. Still, it seems implausible that too low residual percentages are the sole reason for the mismatch as alignment would require residual percentages of up to 400% of the material.

Next to being unrealistically large for allocating all residuals to 'other civil engineering', the presence of some overestimations in monetary units despite the underestimation of physical inputs to construction appear to be a symptom of inaccurate material prices and/or temporal mismatch highlighted above. Inaccuracies in material prices have two potential causes. **On the one hand, the material prices applied here**

may not accurately describe the price of specific material inputs needed for construction. For instance, for plastics, the average unit price of 1 tonne of supply of the rubber and plastics industry as available in BONSAI was applied. However, the products of the rubber and plastics industry are very diverse ranging from toys, tools, packaging to insulation material, whereas significant material contents of plastics in buildings are mainly insulation material, foils and large plastic sheets which may have a considerably lower unit price than average supply of the industry. Similar issues apply to the prices for glass and stone. **On the other hand, material prices may also differ by source country**. For instance, construction wood sawn in Sweden may have a different price than construction wood sawn in China due to differing environmental regulations, labour and distribution costs. Instead, the prices applied here only differ by the country in which the material is used. This limitation is particularly relevant for precisely those materials for which the material prices relate to broader categories than the specific material used for construction (plastic, glass, stone) because in such cases the sourcing structure of the construction material may differ from that which the material prices refer to. Nevertheless, since most of the material inputs to construction – except for basic metals and plastics - are predominantly domestically sourced and the disaggregation relies on the homogenous sourcing assumption (cf. Appendix Figure D1), this second limitation is not as relevant as the former one.

Overall, the combination with top-down data in this study allows to cushion such inaccuracies in the bottom-up estimates. Nevertheless, this cushioning also affects the distinctiveness between subsectors in two ways: First, residuals are distributed across subsectors to avoid attributing all residuals to the ‘other civil engineering’ sector and hence assuming a completely unrealistic production technology. This redistribution of residuals reduces the differences between production technology more than what the initial material intensities would suggest (cf. Appendix Figure E1 and E2 for a comparison with a conservative approach). For instance, without redistribution, roads construction would have less plastic and wood inputs. Secondly, the inaccuracies also made some rebalancing of the production technology necessary to align total inputs with total output, which entailed adjusting the prices of material inputs. The adjustment had a tendency towards lowering material prices in the metal-intensive electricity infrastructure and railway sector while increasing prices in the building sector. Hence, more accurate information on the physical bottom-up estimates might further increase the discrepancy in carbon intensity between subsectors.

5. Outlook & Conclusion

5.1. Data needs for further and more robust bottom-up disaggregation

The exploration of using physical built environment proxies for the disaggregation of a monetary MRIOT reveals multiple data gaps that require further research, standardisation and data collection efforts to ensure a robust and coherent representation of construction in macro-economic models.

5.1.1. Research on physical flows related to the built environment

Industrial ecology, material sciences and construction management research can contribute to the detailing of construction in macro-economic models by increasing the coverage of structures for which material intensities and stocks are reported, further empirically specifying stock and flow dynamics of archetypical structures through lifetimes, residual percentages and onsite recycling percentages, and increasing country and temporal resolution of material intensities.

Construction volume estimates in the pipeline (water and fossil fuel transport), waterway, transmission, and landscaping sector would allow to further differentiate 'other civil engineering' for which detailed production values are already reported (Eurostat, 2024a). Sources for such construction volume estimates could be timeseries of the available satellite-imagery stock estimates (Arderne et al., 2020; Ehalt MacEdo et al., 2022) in combination with lifetimes; or project level data as for instance crowd-sourced by Global Energy Monitor for fossil fuel infrastructure (Global Energy Monitor, 2024). It is crucial to develop such datasets in line with units for which material intensities are available (barrel oil, wastewater treatment capacity, etc.).

Also regarding material inputs, comprehensive information on the material used for archetypical water infrastructure (ports, wastewater treatment plants, etc.) and landscaping (parks, new waterways, extraction site preparation, etc.) is largely absent. Similarly, material content analysis should aim for more geographic variation, for describing archetypical structures rather than particularly innovative buildings, and information on material content in new structures compared to older structures to allow for robust integration in macroeconomic models. Despite the usefulness of material content estimates, there is a discrepancy between the interest of MSA studies and the interest in understanding production technologies. More knowledge on residual percentages and onsite recycling percentages will be necessary to bridge this gap.

The challenge further extends to the timing of inputs to the construction process. Construction activities differ from normal production activities in that the creation of the final product, i.e. the structure or building, usually stretches over several years (Lee & Won, 2021; van Niekerk et al., 2022). Hence, the inputs to the construction sector recorded in one year are not necessarily used for the creation of the value recorded as supply to final demand of that year but also for final demand in following years. In contrast, physical construction volumes based on stock estimates only represent the finished amount of construction in that year. So, calculating physical material inputs by multiplying physical construction volumes with material intensities derived from MSA studies, and integrating these material inputs into the IOT assumes that all material inputs are acquired only in the year in which the structure is finished and sold. To enable a better translation of physical material inputs to the IOT, knowledge on the average construction duration of different structures would be required, as well as knowledge on the specific timing of inputs to the construction process (e.g. it could be assumed that most of the concrete and steel is used in the initial stages of construction, whereas plastic and glass inputs are acquired only in later years).

Finally, introducing information on energy use and onsite emissions during construction by type of structure as for instance available from LCAs (Bahramian & Yetilmezsoy, 2020) in line with the outlined procedure could enable more variance in the production technology. For further improving the representation of service and machinery inputs to different construction subsectors, for which information is usually not available from LCA or MSA studies, the multi-unit procedure could be combined with a monetary approach based on production technology of countries with detailed national IOT such as the USA, Canada or Japan.

5.1.2. International harmonisation of national economic statistics

Records of production value, i.e. total output, of construction subsectors should be further detailed horizontally for instance by differentiating between building construction for residential versus non-residential purposes, combustion power plants versus wind power plants, and motorways versus local roads. Since physical construction volumes and material intensities in the EU are available at this level of granularity, this would allow to further disaggregate the construction sector, better link its supply to other industries, and model more meaningful investment scenarios. Without such information, further detailing of construction subsectors in the MRIOT requires assuming homogenous prices of construction per square metre (or per generation capacity in the case of electricity infrastructure) across construction subsectors (cf. Appendix Figure E3 and Figure F8**.** In order to achieve this higher level of granularity in total output statistics, international standardisation is necessary since national IOT which do show detailed accounts of construction activity use diverging and unclear sector boundaries. Currently multiple standards for classifying construction activities are available, but there is no consensus on which division to use (European Union, 2008; Eurostat, 2008; UN Statistics Division, 2023).

Moreover, as stocks of structures in Europe are aging and retrofits of buildings and infrastructures are required to comply with climate change mitigation and adaptation (Sandberg et al., 2016; Streicher et al., 2021), **maintenance of structures becomes an increasingly relevant component of construction activity next to the creation of new structures**. For transport infrastructure, maintenance and incremental replacement of existing structures already today requires more material inputs per year than the expansion of the road and railway network in the EU (cf. Appendix Figure D5). Nevertheless, there is no clear distinction of construction activities meant for maintenance of structures versus creation of new structures specified in the System of National Accounts (UN, 2008), nor has a common definition developed in practice. In contrast, through the application of material-specific lifetimes, physical material inputs can be differentiated between those used for maintenance vs. expansion. One possibility for differentiating maintenance from new construction in the input-output framework could be by interpreting construction activity recorded as gross fixed capital formation (which requires larger single investments) as construction of new structures, whereas construction activity recorded as intermediate or final consumption could be interpreted as maintenance. Such an interpretation would require accounting consensus among statistical offices.

5.1.3. Cross-cutting research needs

Supply of the construction sector to the construction sector makes a large proportion of the unit cost, as well as the overall climate impact of the construction industry (Figure 3). When disaggregating the construction sector into different subsectors this self-linkage presents a challenge, because it remains unclear whether some of the construction self-linkage would be cross-subsector trade within construction (e.g. the building construction subsector buying inputs from the road construction subsector) or whether all of it would be within the same subsector (i.e. from building construction to building construction). The present study assumes that self-linkage is distributed across subsectors as any other ‘other industry input’. A potential source for information to further clarify this issue could be national IOT which cover a detailed horizontal division of the construction sector such as Canada, the USA, or Japan. Nevertheless, more than a technical issue this also remains a conflict point in modelling between the physical system dynamics perspective which would emphasise the reinforcing dynamic between subsectors in contrast to the economic accounting perspective which focusses on monetary transactions between actors. For instance, the building developer might not pay the road constructor to connect the new building to the transport network, i.e. the actors operate independently from an economic accounting perspective, although both is jointly planned and physically correlates from a system dynamics perspective.

5.2. Future applications of detailed construction sectors in environmental impact assessment

Multiple fields benefit from the availability of a MRIOT with a construction industry detailed using physical proxies. As the disaggregation requires collecting construction volume information in physical and monetary units, the **carbon intensity of each subsector can be expressed per dollar invested as well as per square metre or**

electricity generation capacity built. This, for instance, allows to show that visible cross-country differences in carbon multipliers of construction –which suggest higher carbon intensity in Eastern European countries which more recently joined the EU– are largely explained by differences in purchasing power as these differences are not as stark when calculating the embodied emissions per square meter of building or road construction (cf. Appendix Figure F6). Further, it could favour cities and their local governments who are key decision makers in the decarbonisation of the construction industry but face low availability of transaction data (Seto et al., 2021). A tool that allows to model climate impacts based on construction volumes in floor area could present an important step towards the monitoring of urban carbon footprints and prioritising action across sectors (Heinonen et al., 2020).

Secondly, a MRIOT with a construction industry disaggregated by societal function allows to better **link gross fixed capital formation to its final use in society**. This could be useful for endogenizing built capital in consumption footprints (Södersten et al., 2018) as well as for assessing carbon efficient need satisfiers (Vita, Hertwich, et al., 2019).

Thirdly, the representation of differences in production technology in a multi-regional IOT also allows to better understand **changes in international trade and related virtual emissions that result from investment shifts** in face of elevated efforts to tackle climate change. For instance, the increase in investments in electricity, railway and pipeline infrastructure that is expected to meet EU carbon neutrality targets given the current policy plans (Klaaßen & Steffen, 2023) could double annual infrastructure-related emissions over the next ten years, while outsourcing a greater share of CO_2 emissions and material extraction and processing required for EU construction. This highlights the critical role of exploring demand-side climate mitigation options such as reducing energy demand to avoid further burden shifting to the already strained Global South (Creutzig et al., 2024).

Using the disaggregated MRIOT subsector-specific **demand scenarios could be analysed under which to meet international climate agreements and planetary boundaries**. Here, it would be particularly important to also detail construction in of Asia, South America and Africa where major investment decisions are projected to meet decent living standards of a growing population (cf. Appendix B Transferability of the procedure to other world regions). If consistently compiled for multiple years and if more temporal differentiation of material intensities is achieved, the factors driving impacts in different subsectors of construction could be analysed using structural decomposition analysis.

In all these applications, it is recommended to perform the disaggregation in a MRIOT with a high detail in material inputs such as FIGAROe3, GLORIA or BONSAI to accurately represent the environmental impacts of different construction subsectors.

5.3. Conclusion

This research project addressed a critical gap in understanding the carbon footprint of different societal functions of construction activity by proposing an approach that allows to detail a monetary MRIOT using physical bottom-up estimates. Focusing on the EU, the project offered insights into the carbon footprints of different construction subsectors, the main contributing materials and location of emissions. Overall, this analysis suggests that the main lever for demand-driven CO_2 emission reduction of construction in the EU is in buildings –which dominates the carbon footprint and production value of construction in most EU countries–, while increased investments in the metal-intensive electricity infrastructure, railways and other civil engineering could raise the carbon intensity and outsourced emissions of the construction industry as a whole. Still, it needs to be noted that this analysis only shows which demand is responsible for emissions upstream, not which emissions could be reduced with low effort or what the downstream effects of a change would be. The exploration of integrating physical bottom-up estimates with monetary MRIOT highlights future avenues for research on material stocks, as well as calls for a further standardisation and harmonisation of national accounts. Once these data limitations are addressed, the developed procedure can have broader applications, benefiting urban planning, consumption footprint assessments, and scenario analyses aligned with international climate goals. Ultimately, this research takes another step towards informed decision-making in the construction industry for achieving climate mitigation targets.

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I started exploring the field of Industrial Ecology with lots of curiosity and an ambition to understand the societal processes and configurations that can enable us to stay within a safe and just operating space. Throughout the two years, I was humbled by the limited means that we have to quantify and model the world around us. But I also saw an eager and supportive community that is committed to push these limits. First and foremost, I would like to thank my supervisors Ranran Wang and Stefano Merciai for their continuous support throughout this project. You have opened my eyes to the intricacies of national accounting and the means we have to combine physical information with monetary accounts. My special thanks also go to Edgar Hertwich and Sebastiaan Deetman for thinking along in the initial stages of conceptualising the thesis and for emphasising a feasible scope. Rajib Sinha, Lola Annie-Rousseau, Martijn van Engelenburg, Yi Li, Tomer Fishman and Dominik Wiedenhofer have kindly responded to my requests about their studies which helped me integrate the insights into this work. I would like to thank Mingming Yu for facilitating contact with civil engineers from TU Delft. I hope that this collaboration and be further advanced in the future to achieve a better representation of infrastructure in environmental impact models. I would also like to thank the many contributors to stackoverflow that have enabled me to create the graphs I want. Finally, I am deeply grateful for the mental and physical nourishment that I received from my partner and friends, and the emotional support and deep discussions that we shared. Thank you for letting me see things in the bigger picture.

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Appendices

Appendix A: Literature review

Table A1: Overview of reviewed literature.

Reference	Relevance	Geographical Scope	Geographical Resolution	Temporal Scope	Temporal Resolution	Method	Database	Detail of Construction Sector	Finding	Extension	Supplementary Material	What does my study add
Hertwich & Peters 2009	climate impact of construction sector relative to other sectors	Global	Regional	2001	one year	Leontief demand-pull model	Global Trade Analysis Project (GTAP)	Construction	construction: 10% (3.42 Gt CO2e) of global GHG emissions	CO2e	yes	sectoral detail
Huang et al. 2018	carbon impact of construction sector including material and energy inputs; importance of EU construction	Global	National	2009	one year	Leontief demand-pull model	World Input-Output Database (WIOD)	Construction	construction: 23% (5.7 Gt CO2) of global CO2 emissions; EU construction: 18% (579 Gt CO2) of EU CO2 footprint EU lowest carbon footprint intensity of construction indirect emissions of EU construction: 90% (fossil fuel energy for material production contributes most) EU one of the largest contributors to global emissions of construction after CHN	CO2	no	sectoral detail
Onat & Kucukvar 2020	comprehensive review and comparison of carbon footprint of construction depending on database	China, USA, India, Japan, Canada	National	1990-2012	annual	Literature review Leontief demand-pull model Scope 1,2,3 Supply chain analysis	World Input-Output Database (WIOD), Global Trade Analysis Project (GTAP), Monetary Exiobase, Eora	Construction	most studies focussed on China large differences in the relative importance of direct, indirect regional and indirect global emissions as well as in the relative importance of Scope 1, 2 and 3 emissions between CN, US, IND, JP, CN indirect emissions as share of total: USA (90%), Canada (88%), Japan (88%) large differences in overall footprint of construction depending on database	CO2e	yes	sectoral detail
International Energy Agency 2023	most recent estimate of climate impact of construction industry	Global	Global	2022	annual (but inconsistent boundaries)	carbon intensity & production estimates of high-volume construction materials (cement, steel, and aluminium)	undisclosed	Building construction, Other construction activities	construction: 15% (4.8 Gt CO2) of global CO2 emissions building construction: 8% (2.5 Gt CO2) of global CO2 emissions	CO2	no	comparison between different construction activities
Wang et al. 2023	relevance of construction sector, legacy footprint perspective	Global	National	1995-2019	annual (more years available)	Legacy environmental footprint of manufactured capital	Monetary Exiobase	Construction with Real estate services	construction (in combination with real estate services) largest economic sector contributing to legacy carbon footprint of manufactured capital in 2019 EU LEF of manufactured capita levelling off but still increasing in 2019 (investment growth > investment carbon efficiency increase)	CO2e	yes	sectoral detail
Lavagna et al. 2018	climate impact of residential buildings in EU; unit processes for archetypical buildings in 3 EU climate zones	EU	3 Climate Zones	2010	flat (life cycle assessment)	Life Cycle Assessment & Building Stock Assessment	ecoinvent	Building Archetypes: Single Family per building age cohort; Multi-Family per building age cohort	construction, renovation, demolition: 10% (117 Mt CO2e) of building footprint (including use phase)	CO2e	yes	comparison between different construction activities
Hung et al. 2019	climate impact of construction in one country	Hong Kong	National	2004, 2007, 2011	annual	Leontief demand-pull model	Global Trade Analysis Project (GTAP)	Construction	indirect emissions of HK construction: 97% (esp. Utilities, Manufacturing, Transport & Storage) foreign emissions of HK construction: 75%	CO2	-	sectoral detail
Pomponi & Stephan 2021	climate impact of construction in some countries	UK, Italy, South Africa, India	National	2020	one year	Leontief demand-pull model	Eora	Construction	indirect emissions of construction: UK (92%) and Italy (96%)	CO2, water, energy	yes	sectoral detail
Hertwich 2021	emissions related to material production in construction industry	Global	National	1995-2015	annual	Leontief demand-pull model Endogenisation of capital	Monetary Exiobase	Construction	GHG footprint of construction related to material production: 70%	CO2e	yes	sectoral detail
Bahramian & Yetilmezsov 2020	overview of literature in building life cycle assessment	Global	-	-	-	Literature review of LCA	-	Buildings	embodied energy: 10-75% of energy footprint of buildings in EU	energy	no	comparison between different construction activities
Romanovska et al. 2023	overview of literature in green infrastructure life cycle assessment	Global	-	-	-	Literature Review	-	Green Infrastructure	most (still incomplete) life cycle assessments focus on building components (green roof, green wall) and urban gardens, very few on more complex green infrastructure like parks	CO2e, energy	-	comparison between different construction activities
Olugbenga et al. 2019	overview of literature in rail life cycle assessment		-	-	-	Literature Review	-	Rail Infrastructure	large variation in carbon footprint of rail depends on above ground/below ground construction, studies employ diverse system boundaries	CO2e	-	comparison between different construction activities
Saxe & Kasraian 2020	overview of literature in green infrastructure life cycle assessment		-	-	-	Literature Review Theoretical Proposal	-	Road & Rail Infrastructure	transport infrastructure characterised by long lifetime & only partial end of life, constant remaking of infrastructure	-	-	comparison between different construction activities
Zhang et al. 2020	process-based LCA vs. monetary IOA vs. hybrid LCA-IOA	China	Building	-	-	Life Cycle Assessment Leontief demand-pull model Hybrid IO-LCA	LCA data compiled for this study disaggregated National IOT of China by Zhang & Wang (2016)	2 high-rise buildings	pure IOA < process-based LCA < hybrid IO-LCA carbon footprint estimate	CO2e	-	comparison between different construction activities
Steubing et al. 2022	process-based LCA vs. monetary IOA need for disaggregation of construction sector	Global	National (excluding ROW)	2011	one year (hybrid), otherwise flat (life cycle approach)	Life Cycle Assessment Leontief demand-pull model	Hybrid Exiobase ecoinvent	Construction	"a meaningful comparison of classes F (construction) and N (administrative and support service activities) was not possible because of the small number of matched products" (p. XY)	CO2e	-	sectoral detail

Stadler et al. 2018	how to disaggregate sectors in a multi-regional IOT	Global	National	1995-2011 (with nowcasts for recent years)	annual	Sectoral disaggregation MRIOT construction	Monetary Exiobase	Construction	disaggregation based on IEA, EU and FAO data	CO2e, land, material, labour, water	yes	sectoral detail
Wood et al. 2014	how to disaggregate sectors in a multi-regional IOT	Global	National	1995-2011 (with nowcasts for recent years)	annual	Sectoral disaggregation Harmonisation	Monetary Exiobase	Construction	disaggregation based on IEA, EU and FAO data	CO2e, land, material, labour, water	yes	sectoral detail
Bruckner et al. 2019	how to disaggregate sectors in a multi-regional IOT	Global	National	1995-2013	annual	Sectoral disaggregation physical MRIOT construction	Food and Agriculture Biomass Input-Output Model (FABIO)	-	disaggregation based on physical technical coefficient and trade data from FAOSTAT, IEA (fuel efficiency) and BACI/COMTRADE argument for physical IO: over- and underestimation with monetary values	CO2e	yes	sector focus: construction
Wiebe & Lenzen 2016	how to harmonise disaggregated supply and use tables	Global	National	unspecified	one year	Hamonising supply and use tables without balancing with RAS	Global Resource Accounting Model (GRAM) based on ICIO	-	harmonisation based on prescribed intermediate and final demand and residual values	-	yes	sector focus: construction
Wenz et al. 2015	how to disaggregate sectors in a multi-regional IOT	USA	States	2011	one year	Sectoral disaggregation Regional disaggregation Algorithm	Eora	-	algorithm for disaggregating and balancing IOT based on (inconsistent) proxies: take coarse grained MRIO flows, fine grain them by applying shares derived e.g. from fine-grained GDP-by-industry data	-	-	application
Lenzen 2011	why to disaggregate in IOT	-	-	-	-	Theoretical mathematical proof	-	-	disaggregation superior to aggregation in presence of more detailed environmental extensions	-	-	application
Steen-Olsen et al. 2014	why to disaggregate in IOT	Global	National	1990-2011 (depending on database)	annual	Sensitivity Analysis of Sector Aggregation	Eora Monetary Exiobase GTAP WIOD	Construction	disaggregation superior to aggregation in all 4 databases due to large differences in multipliers (emission footprint intensity)	CO2	yes	application
de Koning et al. 2015	why to disaggregate in IOT	Global	National	-	one year	Sensitivity Analysis of Sector and Regional Aggregation	Monetary Exiobase	Construction	aggregation of materials and extensions leads to uncertainty in results	material extraction, CO2	yes	application
Nässén et al. 2007	process-based LCA vs. monetary IOA, example of disaggregation of construction in an IOT	Sweden	Building	2000	one year (IOT), flat (life cycle approach)	Life Cycle Assessment Leontief demand-pull model Sectoral disaggregation	National Accounts of Sweden	single-dwelling residential buildings, multi-dwelling residential buildings, service buildings, industrial buildings, reconstruction/refurbishment of buildings, civil engineering	LCA-based energy footprint < IO-based energy footprint	CO2, energy	-	multi-regional table, larger geographical scope, inclusion of indirect non-domestic emissions
Acquaye & Duffy 2010	example of disaggregation of construction sector in an IOT	Ireland	National	na	one year	Leontief demand-pull model Sectoral disaggregation	National IOT of Ireland (single-economy IOT)	Ground Works, Structural Works, Services, Finishes, Plant Operation	indirect domestic emissions of IR construction: 83% share of footprint related to civil engineering: 75% civil engineering lower emission intensity than buildings and plant operations	CO2e	-	multi-regional table, larger geographical scope, inclusion of indirect non-domestic emissions
Yu et al. 2017	example of disaggregation of construction sector in an IOT	Australia, ROW	National	2009-2013	annual	Leontief demand-pull Sectoral disaggregation	Australian IO-Lab Eora	residential buildings, non-residential buildings, roads, other civil engineering structures, construction services	emission intensity of civil engineering works much higher than of building construction	CO2e	no	multi-regional table, different world region
Chang et al. 2014	example of disaggregation of construction sector in an IOT based on physical data	China	National	2007	one year	Leontief demand-pull model Sectoral disaggregation	National IOT of China	13 Building types (residential, non-residential, rural, urban, etc.), Other construction (civil engineering)	energy intensity of urban residential buildings higher than of rural residential buildings emission intensity of civil engineering works much higher than of building construction because of higher steel content supply chains of construction products differ significantly	CO2e, energy	no	multi-regional table, different world region
Zhang & Wang 2016	comparison of carbon footprints of different construction products	China	National	1997-2012	every 5 years	Leontief demand-pull model	detailed National IOT of China	urban, rural residential buildings	energy intensity of urban residential buildings higher than of rural residential buildings	CO2, energy	no	multi-regional table, different world region
Crawford et al. 2022	potential input for my database for construction materials	Australia	National	2014-2015	one year (IOT), flat (life cycle approach)	Life Cycle Assessment Input Output Table as background system Capital Endogenisation	Australian Life Cycle Inventory Database Envirnmental Product Declarations detailed National IOT of Australia	Construction	direct emissions, environmental footprints & material intensities of construction materials used in Australia (EPiC) capital endogenisation increases environmental flow intensity by 10-20%	CO2e, energy, water	yes	sectoral detail of construction activities (not materials), multi-regional table, different world region

Dixit 2017	potential input for my database for construction materials	USA	National	2002	one year	Sectoral disaggregation MRIOT construction	National IOT of USA detailed benchmark accounts	Construction	disaggregation of construction material sectors (e.g. iron and steel) based on data by the national statistical office e.g. materials summary, benchmark accounts	energy	no	sectoral detail of construction activities (not materials), multi-regional table, different world region
Dixit & Singh 2018	example of IO-LCA of buildings	USA	Building	2009	one year	Life Cycle Assessment Input Output Table as background system	National IOT of USA detailed benchmark accounts	4 university buildings	disaggregating the cost of construction into material, services, etc. yields higher estimates than aggregated total cost	energy	no	multi-regional table, different world region, macro perspective
Aguilar-Hernandez et al. 2018	why to use multi-unit input-output tables	-	-	-	-	Literature Review	-	-	physical and hybrid input-output still not often used to model circular economy interventions, but necessary especially for residual waste management strategies because low/no economic value of waste (no monetary flows)	-	-	provide a hybrid table for the construction sector
Merciai & Schmidt 2018	example of multi-unit, multi-layer input-output table	Global	National	2011	one year	Construction of hybrid IOT	Hybrid Exiobase	Construction	combining physical and monetary units in one table can be used for consumption-based footprint analysis if the technical coefficients are relative to the units in which intermediate and final demand is given	CO2e etc.	yes	sectoral detail of construction
Towa et al. 2022	how to use multi-unit input-output tables for local footprints	Belgium	Regional	2011	one year	Regional disaggregation Leontief demand-pull model	Hybrid Exiobase	Construction	demonstates potential use of hybrid table for urban and regional planning	CO2e	yes	sectoral detail of construction
Klaaßen & Steffen 2023	EU infrastructure investment need for carbon neutrality scenario	EU	Regional	2020-2050	5 years	Literature review	-	multiple	infrastructure investment need: 300 million € per year.	-	-	footprint of construction
Oxford Economics 2021	output projections for construction industry	Global	Regional	2020-2030	decadal	grey literature Market research	-	Construction	European construction output growth: 2-3% from 2020-2030, higher growth in Eastern Europe	-	-	footprint of construction
Gao et al. 2023	overview of literature on climate impact of construction sector	-	-	-	-	Literature review	-	-	few studies analyse macrolevel carbon footprint of construction industries outside China, USA, UK, Australia	-	-	macrolevel perspective

Appendix B: Model inputs

Data used for the case study are specified in **Table B1** and used as model inputs as elaborated below. The code for the disaggregation and carbon footprint calculation is available on GitHub[3]. The modular structure of the code allows to feed in other data inputs at various steps of the procedure. For instance, a different set of bottom-up estimates of material mass, material prices or base MRIOT can be used for the disaggregation. The units of each variable are annotated in the code to ease replacing data. To run the code, the suitable packages can be installed using the provided yaml file.

Description of model inputs in the case study

Country-specific total output shares are derived from the EU Structural Business Statistics (Eurostat, 2024a) which report the annual production value of each construction subsector in each country in NACE Level 4 classification. These statistics of the production value of construction (and its subsectors) in Euro (Eurostat, 2024a) align within a ±30% range with the total output of construction in EU countries recorded in ICIO in US Dollar (OECD, 2023) when applying a generic exchange rate (Appendix Figure C2). For the horizontal division, 'Specialised construction activities' are allocated to the Construction of Buildings, Roads, Railways, Electricity Infrastructure, and Other Civil Engineering Projects proportional to the respective share in total output.

Physical construction volumes, i.e. total output in physical units, per country is collected from various official records of the EU Statistical Office Eurostat and cross-checked with geographical information system-based data from peer-reviewed studies (van Engelenburg et al., 2024; Wiedenhofer et al., 2024). For construction of buildings, building permit data reported as useful floor area in the EU Short-term Business Statistics (Eurostat, 2024b) is used and adjusted by a delay between the issuing of the permit and the completion/final sale of the construction project of three years (Röck, 2023). Missing data is interpolated. To achieve a higher detail in non-residential buildings and allow better matching between construction subsector supply and intermediate demand by sectors, shares in stocks of floor area of non-residential buildings such as educational buildings or retail buildings are applied to the remaining non-residential buildings (EU Directorate-General for Energy, 2024). For civil engineering structures, an annual timeseries of stocks of road and railway network length (Eurostat, 2024d; Nguyen et al., 2023) and electricity generation capacity (Eurostat, 2024c), respectively, was used. For consistency, replacement of these stocks was calculated using lifetimes specified in the same studies as used for the material content intensity (Deetman et al., 2021; Wiedenhofer et al., 2024) and assuming linear replacement.

For transport infrastructure, **material content intensities** are taken from (Wiedenhofer et al., 2024) who performed a first systematic assessment of material

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[3] Please request access to the following folder: https://github.com/MiraVos/io-construction-detail/tree/adbbeac98d30132941ed49b3faeb31a4e82f570a/submission

content in global road and railway infrastructure. Country-specific material contents are available for the EU-27 member states Germany and Austria. For all other member states, the global average in material content intensities was assumed. For electricity infrastructure including power plants and connected grid infrastructure, generic material content intensities by (Deetman et al., 2021) derived from a review of mainly European LCA studies are applied. Material content intensities of buildings are generated combining three reviews (Röck et al. 2024, Deetman et al. 2020, Marinova et al. 2020) and calculating the median material intensity per building structure (single-dwelling buildings, multi-dwelling buildings, offices, educational buildings, etc.) and region of Europe (cf. Appendix Figure D3 for regional division). A sensitivity analysis of this assumption is performed using the RASMI database material content intensities compiled by (Fishman et al., 2024) (cf. Appendix Figure F7). Residual percentages and recycling percentages to adjust these material content intensities were compiled via literature review and expert elicitation (cf. Appendix B and Table D2).

To convert material inputs from physical units to monetary units compatible with the monetary base MRIOT, use-country specific basic **prices of materials** derived from the multi-unit BONSAI database available for 2016 are used (BONSAI, 2024).

Transferability of the procedure to other world regions

The procedure aims to be replicable for other world regions. This is relevant since major investment decisions are projected in countries of Asia, South America and Africa to meet decent living standards of a growing population. Some of the critical model inputs applied in this study are also available in other world regions. These include the material intensities for transport (van Engelenburg et al., 2024; Wiedenhofer et al., 2024), electricity infrastructure (Deetman et al., 2021) and buildings (Deetman et al., 2020; Fishman et al., 2024; Marinova et al., 2020; Röck, 2023) which have already been applied in global MSA and are available at regional scale. Also, the material prices applied in this study which derive from the BONSAI database are available for 43 countries and 5 world regions (BONSAI, 2024); and the underlying multi-regional input-output table covers 67 countries but lacks country resolution in Sub-Saharan Africa and South-East Asia (OECD, 2023).

Nevertheless, total output and construction volume data is not always reported by statistical offices. The total output of construction at higher levels of detail is only reported in few medium- and low-income countries including Senegal, Cabo Verde, Indonesia, and some Latin American countries (Mexico, Brazil, Colombia, Costa Rica) with different subsector classification. Building permit data used in this study can potentially be replaced with the stock and lifetime-driven approach used for estimating construction volumes of civil engineering structures. While the stock-driven approach using crowd-sourced maps and satellite imagery promises to enable assessments independent of the capacities of the national statistical offices, most of the available empirical stock assessments of buildings and infrastructures are only snapshots for one year rather than timeseries of stocks (Arderne et al., 2020; Ehalt MacEdo et al., 2022; Milojevic-Dupont et al., 2023; Sirko et al., 2021; van Engelenburg et al., 2024; Wiedenhofer et al., 2024).

Table B1: Overview of the model inputs

Input for Variable	Model Input	File name	Original file name	Database	Provider/ Author	Link	Indicator	Unit	Industry Scope	Industry Classification	Industry Resolution	Input Resolution	Denominator	Temporal Scope	Temporal Resolution	Territorial Scope	Territorial Resolution	Method
Z,Y	Supply of construction to sectors	ICIOcp_[year].csv	ICIOcp_[year].csv	Inter-Country Input-Output (ICIO) v2021	OECD	https://www.oecd.org/en/data/datasets/inter-country-input-output-tables.html	trade value	$	Construction (and other sectors)	SNA Section, other industries ISIC Rev. 4	Construction	.	.	1995-2020	annual	67 countries including OECD, EU27	NUTS0	harmonised national accounts
%x	Total supply of construction subsectors	240212_StructuralBusinessStatistics_TotalOutput_Labour_sbs_na_con_r2__custom_9831151_spreadsheet	sbs_na_con_r2__custom_9831151_spreadsheet	SBS - Structural Business Statistics: Annual detailed enterprise statistics for construction (NACE Rev. 2, F)	Eurostat	https://ec.europa.eu/eurostat/databrowser/view/sbs_na_con_r2__custom_9831151/default/table?lang=en	production value (total output)	€	Construction	NACE Rev. 2 Level 4	Development of building projects Construction of residential and non-residential buildings Construction of roads and motorways Construction of railways and underground railways Construction of bridges and tunnels Construction of utility projects for fluids Construction of utility projects for electricity and telecommunications Construction of water projects Demolition Site preparation Test drilling …	.	.	2008-2020	annual	EU-28	NUTS0	official records
x_physical	Construction volume: Buildings	20240212_STS_BuildingPermits_sts_cobp_a_spreadsheet	sts_cobp_a_spreadsheet.xlsx	Short-term Business Statistics Construction Building Permits	Eurostat	https://ec.europa.eu/eurostat/databrowser/product/page/sts_cobp_a	useful floor area	m2	buildings	EU CPA 2.1	Residential building Nonresidential buildings	.	.	2005-2022	annual	EU 27	NUTS0	official records
x_physical	volume share:	uildingPermits_st	adsheet.xlsx	Statistics	Eurostat	pa.eu/eurostat/	area	m2	buildings	EU CPA 2.1	Multi-dwelling building	.	.	2005-2022	annual	EU 27	EU27	official records
x_physical	Construction volume share: Non-residential buildings	240127_BSO_BuildingStock_EU_2016-2020	data0.xlsx	EU Building Stock Observatory	EU Energy, Pezzutto et al.	https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/eu-building-stock-observatory_en	useful floor area	m2	residential & non-residential commercial buildings	archetypes (close to EU CPA)	Single-family building Apartment blocks Office buildings Wholesale and retail trade buildings Hotel and restaurant buildings Health buildings Education buildings Other buildings	.	.	2016	point estimate	EU 27	NUTS0	non-residential building shares derived from hotmaps project 2016
x_physical	Share of maintenance: Buildings	240311_Destatis_BuildingPermit_ShareNewBuildings_Renovation_31111-0001	31111-0001	Baugenehmigungen im Hochbau: Deutschland, Jahre, Bautatigkeiten,Gebaudeart/Bauherr	Destatis	https://www-genesis.destatis.de/genesis/online?levelindex=3&levelid=1710150773449&downloadname=&operation=ergebnistabelleDiagramm&option=diagramm#abreadcrumb	useful floor area	m2	buildings	NACE	Residential building Nonresidential buildings	.	.	2001-2022	annual	Germany	NUTS0	official records
x_physical	Construction duration: Buildings	240307_Roeck-carbenmats-buildings-7557e1f	mroeck-carbenmats-buildings-7557e1f	CarbEnMats-Buildings	Röck et al.	https://doi.org/10.21203/rs.3.rs-3373442/v1	Δ construction end - construction start	years	residential and non-residential service buildings	archetypes	Single family house 526 Multi-family house 325 Office 180 No data 72 Row house 51 School and Daycare 34 Other 29 Semi-detached 26 Retail and Restaurant 21 Hotel & Resort 11 Mixed use 10 Hospital and Health 5 Sport & Entertainment 2 Technology & Science 1 Art & Culture 1	.	.	1940-2025	annual	Western Europe: France Belgium Denmark Finland Italy Austria Sweden Germany Portugal Spain	NUTS0	1-30 cases per building type based on compilation of Systematic Literature Reviews; estimate confirmed by architect from TU Delft

Input for Variable	Model Input	File name	Original file name	Database	Provider/ Author	Link	Indicator	Unit	Industry Scope	Industry Classification	Industry Resolution	Input Resolution	Denominator	Temporal Scope	Temporal Resolution	Territorial Scope	Territorial Resolution	Method
x_physical	Stocks: Roads	240214_Nguyen2023_Roads_Eurostat	1-s2.0-S0921344923000988-mmc1	The stock-service productivity of the European road transport infrastructure	Nguyen et al.	https://doi.org/10.1016/j.resconrec.2023.106961	network length	km	roads	archetypes	Motorways State roads Provincial roads Communal roads	.	.	2010-2019	annual	EU 24	NUTS0	cleaned and interpolated official records from Eurostat cf. Road transport infrastructure at https://ec.europa.eu/eurostat/web/transport/data/database
x_physical	Stocks: Railways	240214_EUROSTAT_RailwayTrackLength_rail_if_tracks_spreadsheet	rail_if_tracks_spreadsheet	Railway transport infrastructure: Length of railway tracks by electrification of tracks	Eurostat	https://ec.europa.eu/eurostat/databrowser/view/rail_if_tracks__custom_9871343/default/table?lang=en	network length	km	railways	archetypes	Electrified railways Non-electrified railways	.	.	1990-2022	annual	EU27	NUTS0	official records
x_physical	Lifetime: Transport infrastructure	240212_Wiedenhofer_2024_MobilityInfrastructure_2021 - full supplementary data	Mobility Infrastructure - full supplementary data	Mapping and modelling global mobility infrastructure stocks, material flows and their embodied greenhouse gas emissions	Wiedenhofer et al.	https://doi.org/10.1016/j.jclepro.2023.139742	service lifetime	years	transport infrastructure	materials	Iron Concrete Asphalt Aggregate Timber Copper Cement Aluminium Other	.	.	.	.	Northern Hemisphere	Global	systematic review of road LCA studies from 12 European and 11 non-European countries, expert opinion, own assumptions
x_physical	Stocks: Electricity infrastructure	240214_EUROSTAT_ElectricityProductionCapacity_nrg_inf_epc_spreadsheet	nrg_inf_epc_spreadsheet	Energy infrastructure and capacities: electricity production capacities by main fuel group and operator	Eurostat	https://ec.europa.eu/eurostat/databrowser/view/nrg_inf_epc__custom_9871714/default/table?lang=en	electricity generation capacity	MW	electricity	Standard international energy product classification (SIEC)	Combustible fuels Hydro power Geothermal Wind on shore Wind off shore Solar thermal Solar PV Tide, wave, ocean Nuclear Other	.	.	1990-2022	annual	EU27	NUTS0	official records
x_physical	Lifetime: Electricity infrastructure	Deetman_2020_MatIntensity_Electricity	1-s2.0-S0921344920305176-mmc2	ELMA: Projected material requirements for the global electricity infrastructure – generation, transmission and storage	Deetman et al.	https://ars.els-cdn.com/content/image/1-s2.0-S0921344920305176-mmc2.pdf	technical lifetime	years	electricity infrastructure	archetypes	Combustible fuels Hydro power Geothermal Wind on shore Wind off shore Solar thermal Solar PV Nuclear Transformers Substations Lines Other	.	.	2007-2014	.	Global (mainly Northern Europe)	.	4 LCA studies and TIMER model
z_base	Inputs used by construction	ICIOcp_[year].csv	ICIOcp_[year].csv	Inter-Country Input-Output (ICIO) v2021	OECD	https://www.oecd.org/en/data/datasets/inter-country-input-output-tables.html	trade value	$	Construction (and other sectors)	SNA Section, other industries ISIC Rev. 4	Construction			1995-2020	annual	67 countries including OECD, EU27, major trade partners	NUTS0	harmonised national accounts

Input for Variable	Model Input	File name	Original file name	Database	Provider/ Author	Link	Indicator	Unit	Industry Scope	Industry Classification	Industry Resolution	Input Resolution	Denominator	Temporal Scope	Temporal Resolution	Territorial Scope	Territorial Resolution	Method
mi	Material content: Buildings	240307_Roeck-carbenmats-buildings-7557e1f	mroeck-carbenmats-buildings-7557e1f	CarbEnMats-Buildings	Röck et al.	https://doi.org/10.21203/rs.3.rs-3373442/v1	material input	kg/m2	residential and non-residential service buildings	archetypes	Single family house Multi-family house Office No data Row house School and Daycare Other Semi-detached Retail and Restaurant Hotel & Resort Mixed use Hospital and Health Sport & Entertainment Technology & Science Art & Culture	Top 5 Materials out of: Aluminium Bamboo Brass & Copper Cement & Mortar & Plaster Ceramics Reinforced Concrete Non-reinforced Concrete Earth & Clay Polystyrene Insulation Fungi Glass Iron & Steel Metals Plastics Reinforcing Steel Stone Stone Wool Insulation Straw & Hemp Timber & Wood Other	building (but m2 available)	1940-2025	annual	Western Europe: France Belgium Denmark Finland Italy Austria Sweden Germany Portugal Spain	NUTS0	1-92 cases per material, and 1-30 cases per building type based on compilation of Systematic Literature Reviews
mi	Material content: Residential buildings	240212_Marinova_2020_MatIntensity_Residential		Global construction materials database and stock analysis of the residential buildings between 1970-2050	Marinova et al.	https://doi.org/10.1016/j.jclepro.2019.119146	material content per building	kg/m2	residential buildings	archetypes (close to EU CPA)	Detached residential buildings, urban/rural Semi-detached residential buildings, urban/rural Appartment blocks, urban/rural High-rise residential buildings, urban/rural	Steel Concrete Aluminium Copper Wood Glass	m2 useful floor area	1900-2012	.	Global (Europe)	IMAGE regions (Western Europe; Eastern Europe); and more specific for each data point	100 data points in Western Europe and 25 data points in Eastern Europe per building archetype based on systematic review of available estimates from MSA/LCA studies including ecoinvent and individual case studies
mi	Material content: Non-residential buildings	Deetman_2020_MatIntensity_Nonresidential	1-s2.0-S0959652619335280-mmc1.docx	Modelling global material stocks and flows for residential and service sector buildings towards 2050	Deetman et al.	https://doi.org/10.1016/j.jclepro.2019.118658	material content per building	kg/m2	residential & non-residential service buildings	archetypes (close to EU CPA)	Office buildings Retail buildings Hotel buildings Governmental buildings	Steel Concrete Aluminium Copper Wood Glass	m2 useful floor area	1993-2017 (time of study)	.	USA, Germany, Spain, Mexico, Japan, Thailand, Sri Lanka	NUTS0 (but only single data points)	3-6 cases per building type based on systematic review of available estimates from MSA/LCA studies including ecoinvent and individual case studies
mi	Material content: Buildings (Alternative)			RASMI: Regional Assessment of Buildings' Material Intensity, RASMI: Global ranges of building material intensities differentiated by region, structure, and function	Fishman et al.	https://doi.org/10.1038/s41597-024-03190-7	material content per building	kg/m2	residential & non-residential buildings	archetypes & structural types	Residential single family (detached, row house) Residential multi family (low, high, tower) Non-residential (offices, retail, factory, warehouse, civic) Informal Unspecified	Concrete Steel Brick Wood Glass Copper Aluminium Plastics	m2 useful floor area			EU-15 (before 2004) EU new (high income) EU new (medium income) … other non-EU regions	SSP Regions	1-92 cases per material, and 1-30 cases per building type based on compilation of Systematic Literature Reviews
mi	Material content: Transport infrastructure	240212_Wiedenhofer_2024_MobilityInfrastructure_2021 - full supplementary data	Mobility Infrastructure - full supplementary data	Mapping and modelling global mobility infrastructure stocks, material flows and their embodied greenhouse gas emissions	Wiedenhofer et al.	https://doi.org/10.1016/j.jclepro.2023.139742	material content per surface area of transport infrastructure	t/m2	transport infrastructure	archetypes	Motorways Primary roads Secondary roads Tertiary roads Local roads Rural roads Bridge per road type Tunnel per road type Airplane runways (flexible) Airplane runways (rigid) Railways Railway bridges Railway tunnels Subway underground Subway elevated Subway groundlevel Tram Other rail	Iron Concrete Asphalt Aggregate Timber Other	surface area = network legth * width	2021 (publication for DE, AT), 2000-2024 (publications for global average)	.	Germany Austria UK Turkey Global … other non-European countries	NUTS0	per country systematic reviews and single case studies

Input for Variable	Model Input	File name	Original file name	Database	Provider/ Author	Link	Indicator	Unit	Industry Scope	Industry Classification	Industry Resolution	Input Resolution	Denominator	Temporal Scope	Temporal Resolution	Territorial Scope	Territorial Resolution	Method
mi	Material content: Power plants	Deetman_2020_MatIntensity_Electricity	1-s2.0-S0921344920305176-mmc2	ELMA: Projected material requirements for the global electricity infrastructure – generation, transmission and storage	Deetman et al.	https://github.com/SPDeetman/ELMA/blob/master/Storage_cost/composition_generation.csv	material input/content per MW of electricity generation capacity	kg/MW	electricity	archetypes	Solar PV Concentrated solar power Wind onshore Wind offshore Hydro Other renewables Nuclear Conventional Coal Conventional Oil Conventional Natural Gas Waste IGCC OGCC NG CC Biomass CC Coal + CCS Oil/Coal + CCS Natual Gas + CCS Biomass + CCS all with/without CHP	Concrete Steel Aluminium Lead Glass Copper Cobalt Neodymium	electricity generation capacity	2007-2020	.	Global	.	based on around 30 MFA/LCA studies
mi	Material content: Grid	Deetman_2020_MatIntensity_Electricity	1-s2.0-S0921344920305176-mmc2	ELMA: Projected material requirements for the global electricity infrastructure – generation, transmission and storage	Deetman et al.	https://github.com/SPDeetman/ELMA/tree/master/grid_data	material input per grid line	kg/km	electricity grid lines	archetypes	High voltage Medium voltage Low voltage all under- and above ground	Concrete Steel Aluminium Copper Lead Glass	network length	2010-2014 (time of study)	.	Global	.	based on 3 LCA case studies of different types of electricity power lines
mi	Residual percentage: Buildings & Electricity Infrastructure	.	.	cf. Appendix Table D2	.	.	supply-to-construction residual percentage	% mass	buildings	.	.	Concrete Steel Brick Tiles Mortar Timber Aggregate Stones	.	1996-2017	.	Netherlands Jordan Hong Kong USA Canada Nigeria	.	review of literature and construction management guidebooks
mi	Residual percentage: Transport Infrastructure	.	.	Project data	Li, YI	.	supply-to-construction residual percentage	kg/km	roads	archetypes	Motorways	Asphalt concrete	network length	2024	.	Netherlands	.	inquiry of project level data from two road construction contractors
mi	Onsite recycling percentage: Transport infrastructure	.	.	Project data	Li, Yi	.	onsite recycling percentage	% mass	roads	.	.	Asphalt concrete Aggregates	.	.	.	Netherlands	.	expert elicitation with road engineer
p	Material prices	240411_Merciai_BONSAI_prices.xlsx	prices.xlsx	BONSAI	Merciai et al	https://bonsai.uno	basic price of use	€/kg	.	.	.	Stone Sand and clay Wood and straw (except furniture) Rubber and plastic products Glass and glass products Bricks, tiles and construction products Other non-metallic mineral products Aluminium and aluminious products Lead, zinc and tin and products Copper products Other non-ferrous metal products Fabricated metal products	.	2016	annual	EU-27 +	NUTS0	hybrid MRIOT

Input for Variable	Model Input	File name	Original file name	Database	Provider/ Author	Link	Indicator	Unit	Industry Scope	Industry Classification	Industry Resolution	Input Resolution	Denominator	Temporal Scope	Temporal Resolution	Territorial Scope	Territorial Resolution	Method
m	Multipliers physical material	240605_BONSAI_ghg_for_all_iluc.csv	ghg_for_all_iluc.csv	BONSAI	Merciai et al	https://bonsai.uno	GHG footprint of use	kgCO2 eq./tonne	.	.	.	Stone Sand and clay Wood and straw (except furniture) Rubber and plastic products Glass and glass products Bricks, tiles and construction products Other non-metallic mineral products Aluminium and aluminious products Lead, zinc and tin and products Copper products Other non-ferrous metal products Fabricated metal products	.	2016	annual	EU-27 +	NUTS0	hybrid MRIOT
m	Multipliers monetary material	240717_FIGARO_co2_multiplier,csv	co2_multiplier.csv	FIGAROe3	Cazcarro et al.	https://publications.jrc.ec.europa.eu/repository/handle/JRC137091	GHG footprint of use	kgCO2 / €	.	.	.	Stone Sand and clay Wood and straw (except furniture) Rubber and plastic products Glass and glass products Bricks, tiles and construction products Other non-metallic mineral products Aluminium and aluminious products Lead, zinc and tin and products Copper products Other non-ferrous metal products Fabricated metal products	.	2015	annual	EU-27 +	NUTS0	disaggregated MRIOT for 213 products

Appendix C: Supply of construction and subsectors

This appendix provides additional information on the supply of construction and subsector construction in the EU in physical and monetary units. **Table C1** outlines the subsectors and corresponding structures for which data was collected. **Figure C1** shows the number of physical construction volume datapoints available for each year. The period 2011-2018 had the highest data availability. **Figure C2** shows that there are some notable differences (Sweden, Greece, Romania, Slovakia) between total output recorded in ICIO and production value recorded in official EU statistics, while for most countries seem to align between the two statistics. For this reason, only the shares in production value (not the absolute production value) as recorded in the EU SBS was used to disaggregate the supply of construction recorded in the base MRIOT ICIO as shown in **Figure C3**. Across the 2010s, the subsector composition of total output was relatively constant in the EU with building construction continuously dominating as shown in Figure C3 which speaks for the robustness of the main conclusions regarding the composition of the carbon footprint. Yet, the structure composition of electricity infrastructure varied throughout the 2010s as shown in **Figure C4**. Expansion and maintenance of combustible fuel power plants dominated in 2018 but was overtaken by wind power plants and solar power plants in other years of the 2010s. Most construction of buildings during the 2010s was in residential buildings, especially single-dwelling buildings. For transport infrastructure, local roads including communal and provincial roads occupy the largest share in stocks. **Figure C5** shows the structure composition of buildings, electricity infrastructure and roads for each EU member state in 2018 which was used to calculate the physical bottom-up estimate of material, mat, that forms the basis of the disaggregation. The split between single-dwelling and multi-dwelling buildings does not vary between countries as it was only available at the EU-level.

Table C1: Construction subsectors and related structures according to the horizontal division applied in this study. Other names for structures: names used by material intensity or construction volume datasets which were assumed to correspond to the structures specified.

Subsectors	Structures - default	Other names for structures
Construction of Buildings	Buildings, dwelling multi	Multi-dwelling building, Residencies for communities, Apartment blocks, High rise residential buildings
Construction of Buildings	Buildings, dwelling single	Single-family building, Single-dwelling building, Detached residential buildings, Semi-detached building
Construction of Buildings	Buildings, offices	Office buildings

Construction of Buildings	Buildings, education	Education buildings, School and day care buildings
Construction of Buildings	Buildings, trade	Wholesale and retail trade buildings, Retail and restaurant buildings
Construction of Buildings	Buildings, other	Hotel buildings, Health buildings, Governmental buildings, Other buildings
Construction of Roads	Roads, motorway	Motorways
Construction of Roads	Roads, state	Primary roads, Secondary roads, Tertiary roads
Construction of Roads	Roads, provincial	Rural roads
Construction of Roads	Roads, communal	Local roads
Construction of Railways	Railways	Electrified railways, Non-electrified railways
Construction of Electricity Infrastructure	Electricity, combustible fuels	Conventional coal, Conventional oil, Conventional natural gas, IGCC, OGCC, NG CC, Coal + CCS, Oil/Coal + CCS, Natual Gas + CCS
Construction of Electricity Infrastructure	Electricity, hydro	Hydro
Construction of Electricity Infrastructure	Electricity, nuclear and other fuels	Nuclear
Construction of Electricity Infrastructure	Electricity, wind	Wind onshore, Wind offshore
Construction of Electricity Infrastructure	Electricity, solar photovoltaic	Solar PV, Concentrated solar power
Construction of Electricity Infrastructure	Electricity, other renewables	Waste, Biomass
Construction of Other Civil Engineering	Other civil engineering	

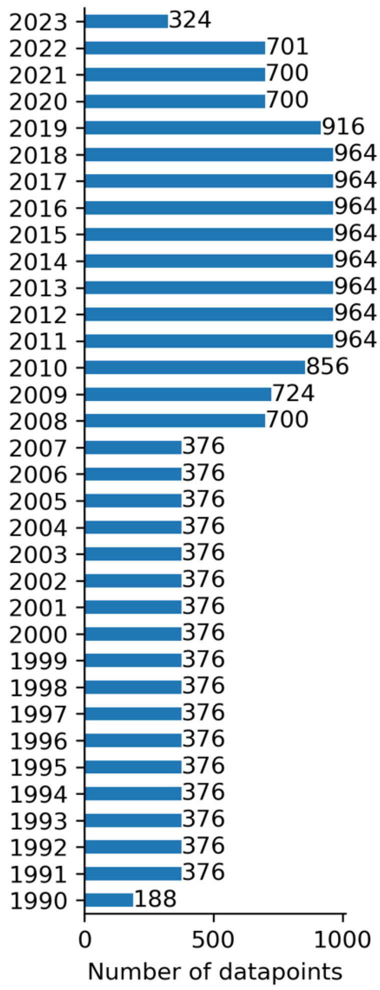


Figure C1: Number of datapoints available in the consulted official EU statistics of physical construction volumes (*x_physical*) across subsectors per year.

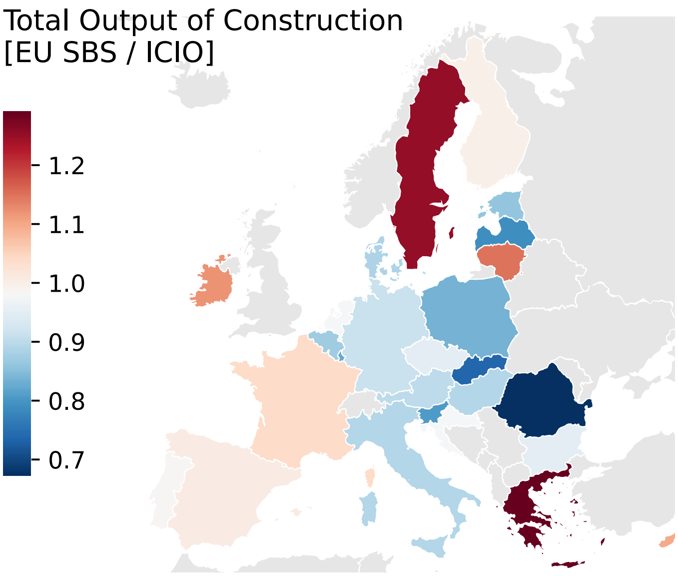


Figure C2: Differences in total output (*x*) of construction recorded in EU Structural Business Statistics (SBS) and OECD ICIO in 2018. EU SBS is converted to US dollar using an exchange rate of 1.18 $/€.

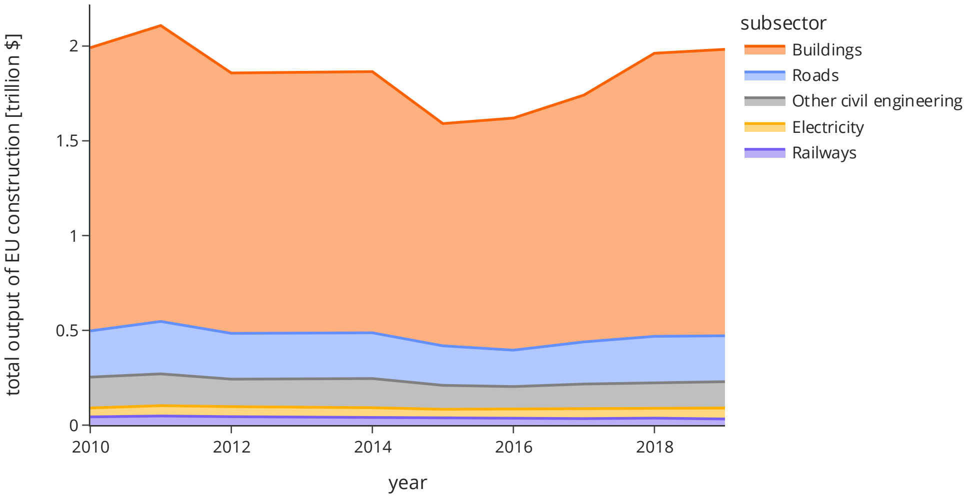


Figure C3: Total output (*x*) of construction in the EU-27 by subsector over the period 2010 to 2019. Totals correspond to ICIOv2021, composition is derived from EU Structural Business Statistics.

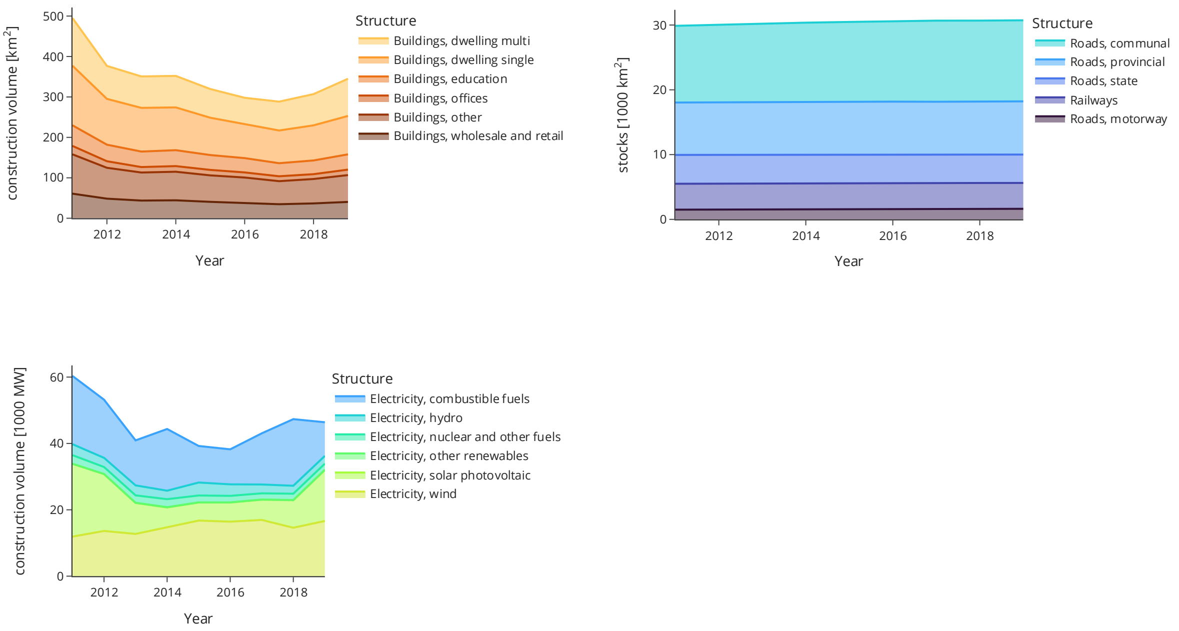


Figure C4: Construction volume (*x_physical*) of buildings (upper left) and electricity infrastructure (lower left) including expansion and maintenance, and stocks of transport infrastructure (upper right) in the EU-27 from 2010 to 2019.

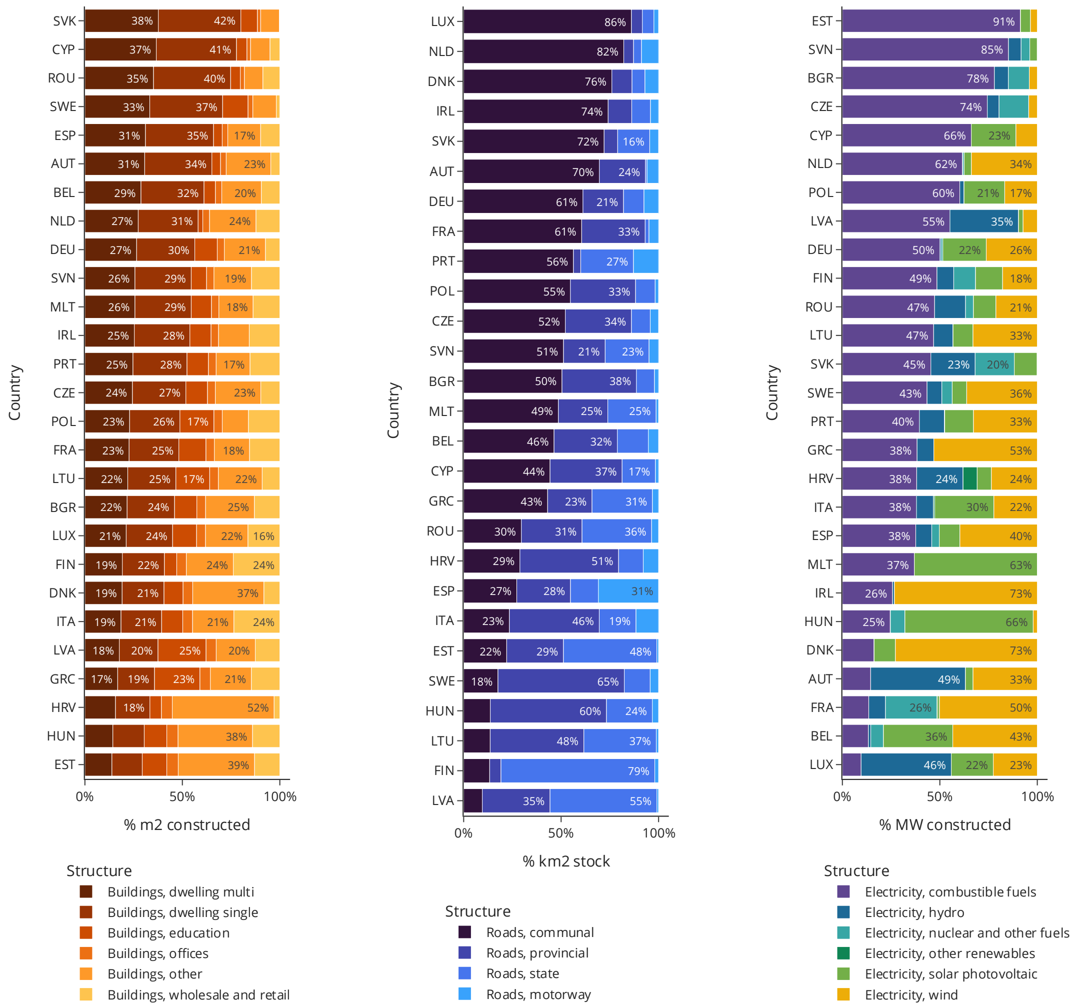


Figure C5: Structure composition of the construction volume (*x_physical*) including expansion and maintenance of the subsectors buildings (left) and electricity infrastructure (right), and of the stock of roads (middle) in each EU-27 country in 2018.

Appendix D: Material inputs to construction and subsectors

This appendix provides additional information on the material inputs to construction and subsector construction in the EU. **Table D1** outlines the input sectors and corresponding materials for which bottom-up data was collected, which focus on material inputs as these are particularly strong contributors to the carbon footprint of construction (cf. Appendix E). **Figure D1** shows that these specified construction inputs tend to be sourced domestically –except for basic metals and plastics– or from within the EU which justifies assuming homogenous sourcing across construction subsectors. **Figure D2** summarises the harmonised material intensities of each structure assumed in this study for the EU based on the sources specified in Table B1 under 'mi'. Material intensities used in calculation of the mass of material inputs, mat, are yet more country and region specific: for buildings, a separation of the EU in three regions is applied as depicted in **Figure D3**. The material content intensities from the sources in Table B1 were adjusted by the median residual percentages specified in **Table D2**. **Table D3** shows the physical bottom-up estimate of total material mass used for construction of buildings, roads, railways, and electricity infrastructure. The accompanying text describes the divergence and alignment of these estimates from estimates reported by industry associations and governmental reports. **Figure D4** shows how this initial estimate of material mass is distributed across structures and subsectors, and **Figure D5** the split between maintenance and expansion of structures.

Table D1: Key material input sectors with corresponding materials for which data in physical units was collected, and corresponding sectors in BONSAI and FIGARO that were used for material-specific multipliers and material prices.

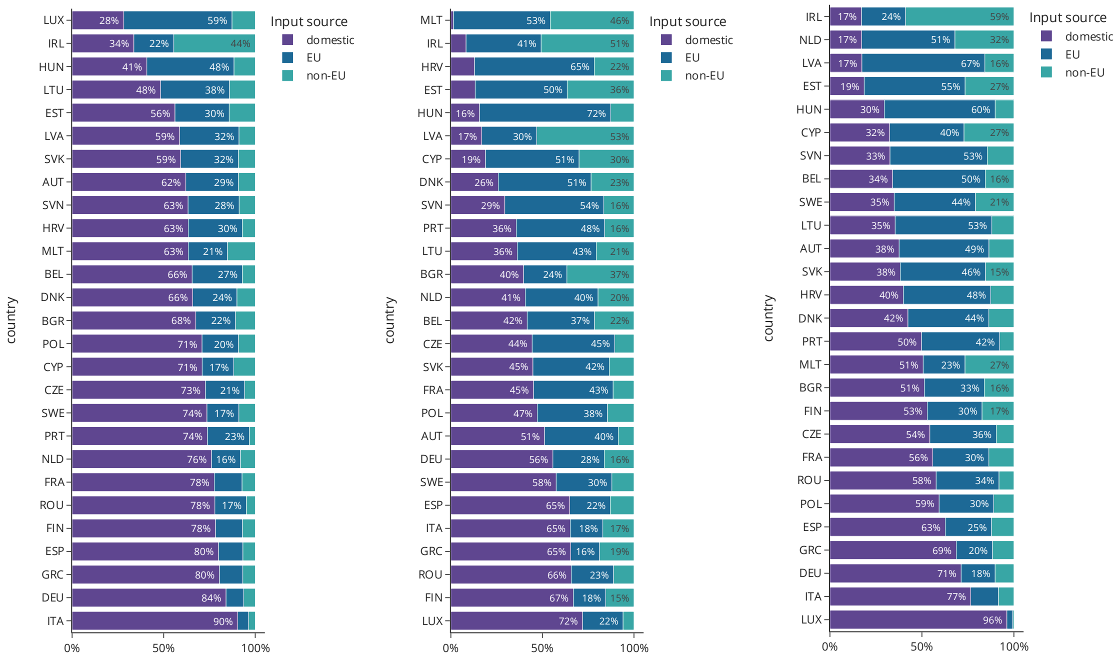
ICIO sector	Material	Other names for material	BONSAI & FIGARO sector
Basic metals	Aluminium		Aluminium and aluminium products
Basic metals	Copper	Brass	Copper products
Basic metals	Lead		Lead, zinc and tin and products thereof
Basic metals	Other metals	Cobalt, Neodymium	Other non-ferrous metal products
Fabricated metal products	Steel	Iron	Fabricated metal products, except machinery
Fabricated metal products	Aluminium		Aluminium and aluminium products
Fabricated metal products	Copper	Brass	Copper products
Fabricated metal products	Lead		Lead, zinc and tin and products thereof

Fabricated metal products	Other metals	Cobalt, Neodymium	Other non-ferrous metal products
Mining and quarrying, non-energy producing products	Sand and clay	Aggregate, Unfired clay, Adobe, Rammed earth	Sand and clay
Other non-metallic mineral products	Concrete		Sand and clay & Cement, lime, plaster
Other non-metallic mineral products	Asphalt concrete		Sand and clay & Cement, lime, plaster
Other non-metallic mineral products	Mortar	Cement mortar, Plaster	Cement, lime, plaster
Other non-metallic mineral products	Bricks	Ceramics, Tiles	Bricks, tiles and construction products
Other non-metallic mineral products	Stone	Granite, Limestone, Mineral wool	Stone
Other non-metallic mineral products	Glass		Glass and glass products
Rubber and plastics products	Plastics	EPS, XPS, PC, PE, PP, PU, PVC	Rubber and plastic products
Wood and products of wood and cork	Timber	Bamboo, Strawbale	Wood and straw (except furniture)

Mining and quarrying, non-energy producing products
Direct sourcing for construction [% USD]

Wood and products of wood and cork
Direct sourcing for construction [% USD]

Other non-metallic mineral products
Direct sourcing for construction [% USD]



Fabricated metal products
Direct sourcing for construction [% USD]

Basic metals
Direct sourcing for construction [% USD]

Rubber and plastic products
Direct sourcing for construction [% USD]

Figure D1: Direct sourcing of key material inputs (*z_mat_base*) to construction in each EU member state in 2018 according to ICIOv2021. Domestic: the country of construction; EU: any other EU-27 member state; non-EU: any other country.

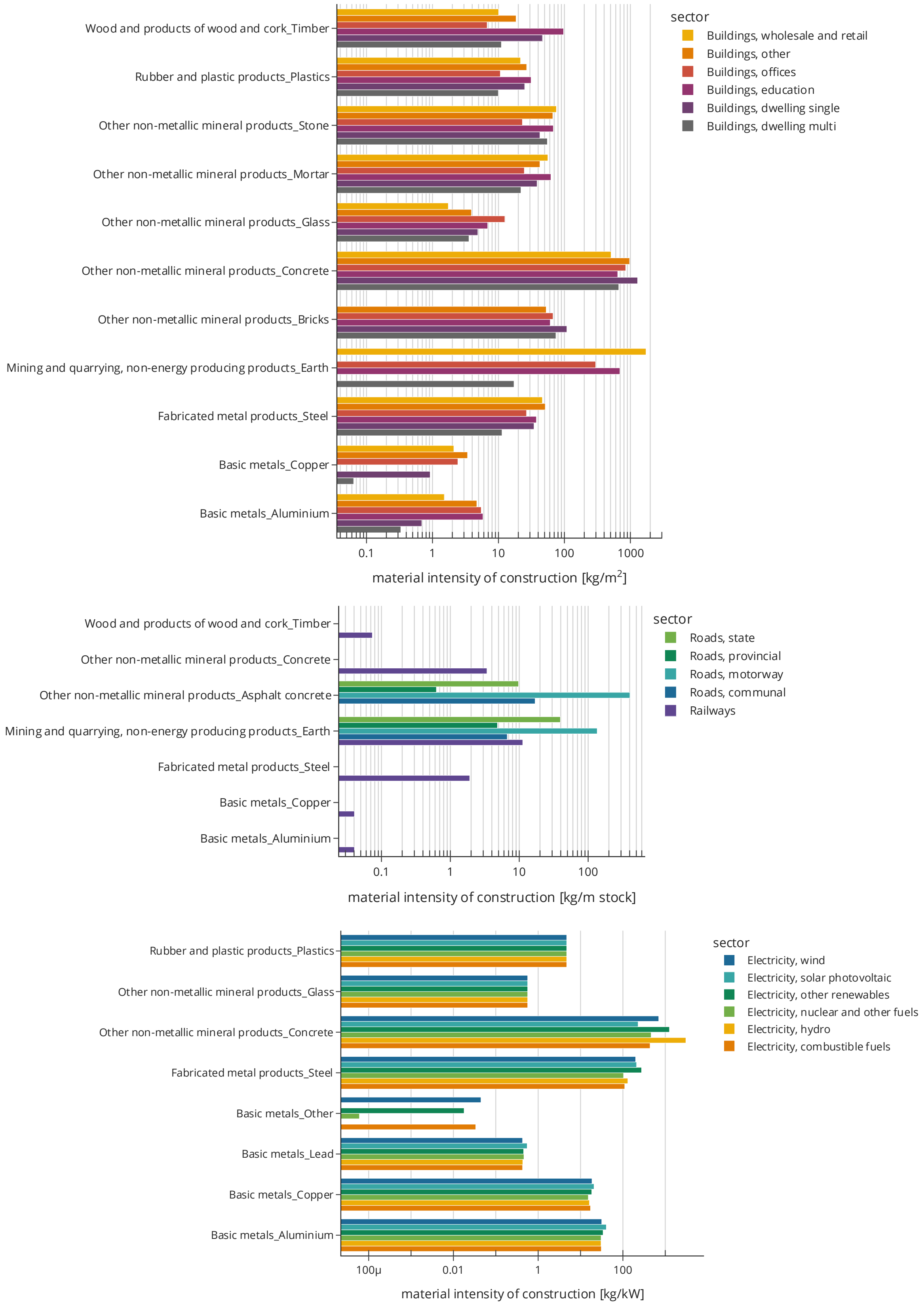


Figure D2: Material intensity (*mi*) of detailed construction subsectors: a) per expansion and maintenance of useful floor area of building type, b) per stock of transport infrastructure types, c) per expansion or maintenance of electricity generation capacity of electricity infrastructure types.

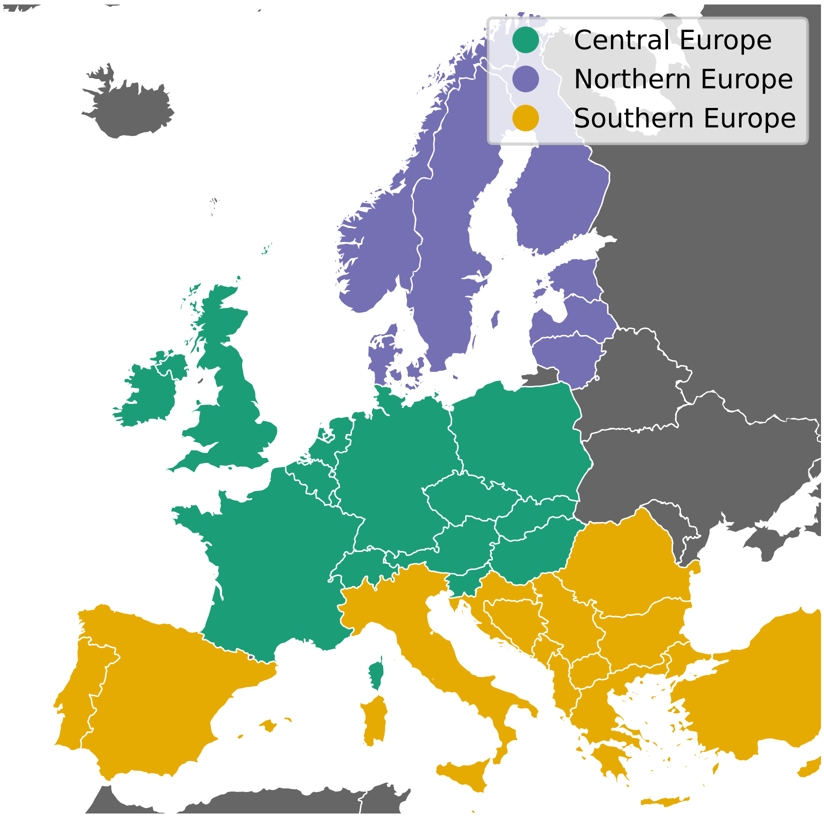


Figure D3: Classification of European countries by region used for differentiating building material intensities (*mi*).

Table D2: Residual percentages, as percent mass, of specified materials based on available literature.

Material	Minimum	Median	Maximum	Source
Aggregates	1%	**11%**	21%	(Bekr, 2014; Bossink & Brouwers, 1996)
Bricks	2%	**6%**	10%	(Bekr, 2014; Bossink & Brouwers, 1996; Cochran et al., 2007; Poon et al., 2001; Tam et al., 2007; Ugochukwu et al., 2017)
Concrete	2%	**5%**	17%	(Bekr, 2014; Bossink & Brouwers, 1996; Poon et al., 2001; Tam et al., 2007; Ugochukwu et al., 2017)
Mortar	10%	**10%**	10%	(Bossink & Brouwers, 1996)
Steel	1%	**5%**	17%	(Bekr, 2014; Poon et al., 2001; Tam et al., 2007; Ugochukwu et al., 2017)
Stones	9%	**12%**	15%	(Bekr, 2014; Bossink & Brouwers, 1996)
Tiles	3%	**7%**	16%	(Bekr, 2014; Bossink & Brouwers, 1996; Tam et al., 2007; Ugochukwu et al., 2017)
Timber	3%	**8%**	20%	(Bekr, 2014; Poon et al., 2001; Tam et al., 2007; Ugochukwu et al., 2017)
Plastics	20%	**20%**	20%	(Bekr, 2014)

Table D3: Bottom-up estimates of mass of material (*mat*) used for construction of buildings, roads, railways and electricity infrastructure based on different sets of building material intensity and different transport construction volumes. Differences from the default are highlighted in bold.

		Building material intensities	Building material intensities	Transport construction volume
Material input to construction (excluding other civil engineering) in Million tonnes	default	**RASMI median (Fishman et al. 2024)**	**RASMI 75th percentile (Fishman et al. 2024)**	**stocks scaled to Wiedenhofer et al. (2023)**
Aluminium	2.271	**1.717**	**1.898**	2.271
Copper	1.286	**0.930**	**0.957**	1.286
Lead	0.021	**0.021**	**0.021**	0.021
Other metal	0.001	**0.001**	**0.001**	0.001
Steel	20.009	**22.015**	**30.820**	20.009
Sand and clay	149.224	**57.542**	**57.542**	**186.508**
Asphalt concrete	145.569	82.649	82.649	**329.611**
Bricks	21.259	**96.714**	**157.509**	21.259
Concrete	304.184	**228.800**	**313.512**	304.184
Glass	1.406	**0.718**	**1.138**	1.406
Mortar	12.075	-	-	12.075
Stone	17.328	-	-	17.328
Plastics	6.756	**0.598**	**1.141**	6.756
Timber	10.341	**11.666**	**17.719**	10.341

For steel, glass and timber, total production volumes of the specific types of materials used for construction reported by industry associations tend to be roughly three times larger than the amount of material estimated in this study. For steel, the European Steel Association reports supply of around 73 Mt steel to the construction industry in 2021 and 2022 with a rising trend ((Eurofer, 2023) p. 23). In contrast, this study estimates only 17-30 Mt steel consumption by the specified construction sectors in the EU-27 in the 2010s with a declining trend. Further, Glass for Europe reports 10 Mt annual flat glass production (80% of this supply is in the building industry) (Glass for Europe, 2024). In contrast, this study only estimates 1-3 Mt glass inputs to construction in the 2010s. One reason might be the omission of greenhouses, as well as an underestimation of residual percentage i.e. the amount of glass that breaks from production to assembly. Estimates of construction **timber** consumption in the EU are rarely reported in mass units and hence are subject to some uncertainty due to conversion from volume to mass. The European Organisation of the Sawmill Industry (EOS) reports a demand for sawn wood in its European member states of around 70 million m^3 in 2018 which translates to roughly

30Mt assuming the density of pine wood (EOS, 2023). (FAO, 2024) reports comparable figures for EU-27 production of sawnwood, while this study only estimates around 9-19Mt of wood input to buildings, railways, and electricity infrastructure during the 2010s. Similar proportions are present when comparing the estimates for the Netherlands with mass of material recorded as construction sector inputs in the Dutch Physical Input-Output Table for 2018 (steel: 34%, glass: 44%, timber: 26%, bricks: 25%) (Delahaye et al., 2023).

The estimates for concrete and asphalt concrete use by the four construction subsectors in the EU also appear at least one third lower when comparing with figures reported by the industry associations. The European Cement Association Cembureau reports 154 Mt in 2016 and 170 Mt in 2021 of cement consumption in EU-27 countries (Cembureau, 2016, 2023). Assuming a 16% cement content per tonne of concrete, this would translate to roughly 1000 Mt annual concrete consumption. In contrast, the disaggregation procedure only finds 230-640 Mt concrete and mortar used for construction in building, road, rail and electricity infrastructure construction under different sets of material intensities of buildings during the 2010s (Deetman et al., 2020; Fishman et al., 2024; Marinova et al., 2020; Röck, 2023). For roads, total **asphalt** concrete production estimated in this study is only roughly two thirds of EU-27 annual production volume reported by the European Asphalt Pavement Association for 2012 to 2019 (EAPA, 2024).

However, in comparison with the Dutch Physical Input-Output Table, **the use of concrete and asphalt concrete, as well as stone and copper, in Dutch construction estimated in this study are rather close** (within a 20% range). Similarly, a study for the EU Directorate-General of Environment focussing on material use for buildings only estimated annual use of concrete for building construction of 662 Mt during the 2000s and 5.5Mt of glass which would align better with the model estimates and is a reasonable comparison given that glass is mainly used for building construction (Figure 7) (Herczeg et al., 2014). However, for timber and steel, (Herczeg et al., 2014) also estimates considerably higher material use than calculated by this study.

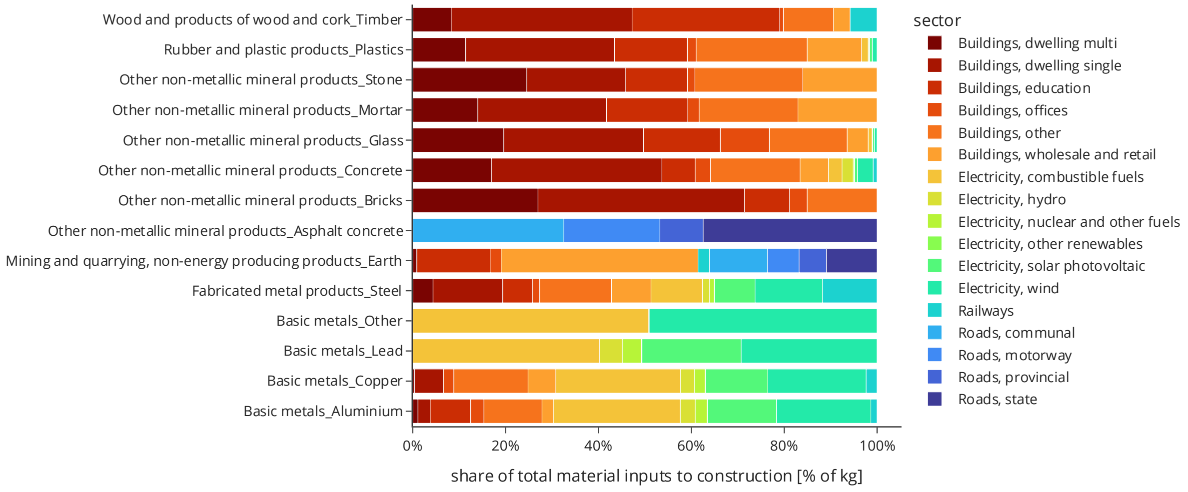


Figure D4: Distribution of the total bottom-up estimate of mass of material inputs (*mat*) to construction by structure in the EU-27 in 2018.

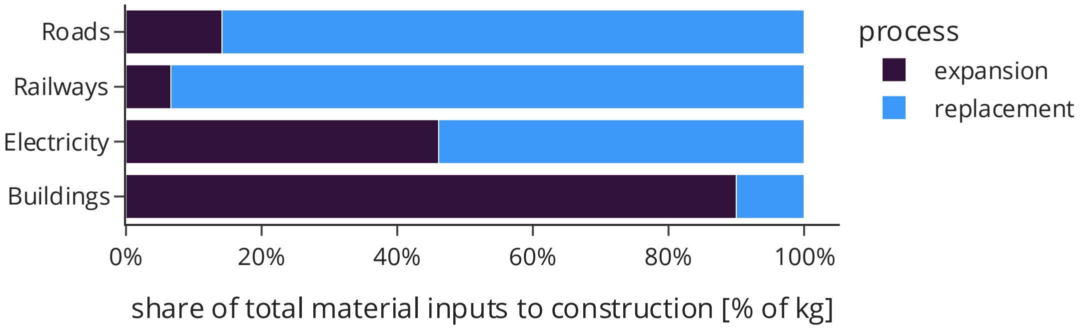


Figure D5: Bottom-up estimate of total material inputs to construction of four subsectors by type of construction activity: mass of material used for construction of new structures vs. used for maintenance and replacement of existing structures.

Appendix E: Input composition of construction subsectors

This appendix provides additional information on the production technology of construction subsectors in the EU under different assumptions. **Figure E0** shows the difference in material inputs between the bottom-up estimate of material inputs expressed in monetary units and the value recorded in ICIO. **Figure E1** shows how the amount of inputs per total output in monetary units assumed based on the bottom-up estimate of material inputs and subsector specific value added is adjusted in the default case by distributing residuals and balancing total input with total output by optimising material prices and other industry inputs. The lowest panel of Figure E1 summarizes the resulting production technology that is used to calculate the subsector carbon footprint. **Figure E2** shows how this distribution differs if assuming that residuals are distributed based on the bottom-up estimate of material input (instead of equally across subsectors). **Figure E3** shows the resulting production technology in the default case per structure assuming homogenous prices of construction supply per square metre (or per generation capacity in the case of electricity infrastructure) within each construction subsector.

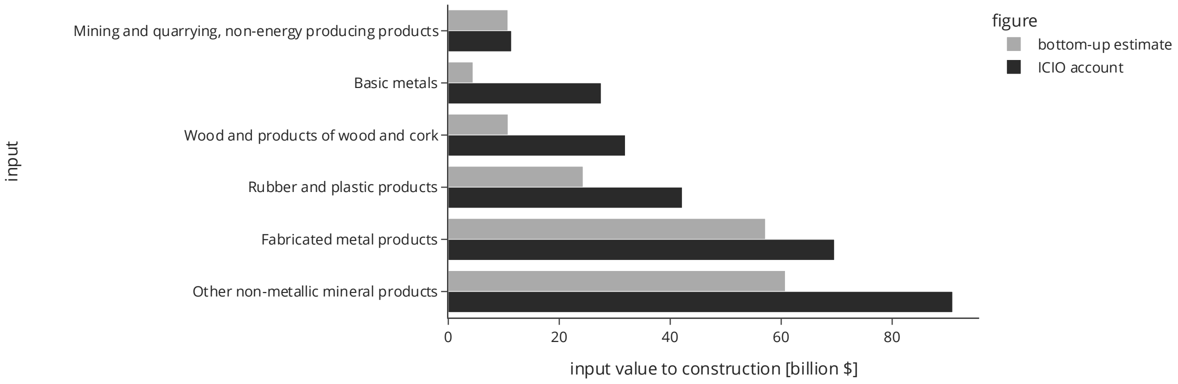


Figure E0: Difference between bottom-up estimate of material inputs expressed in monetary units and the value recorded in ICIOv2021 for EU construction in 2018.

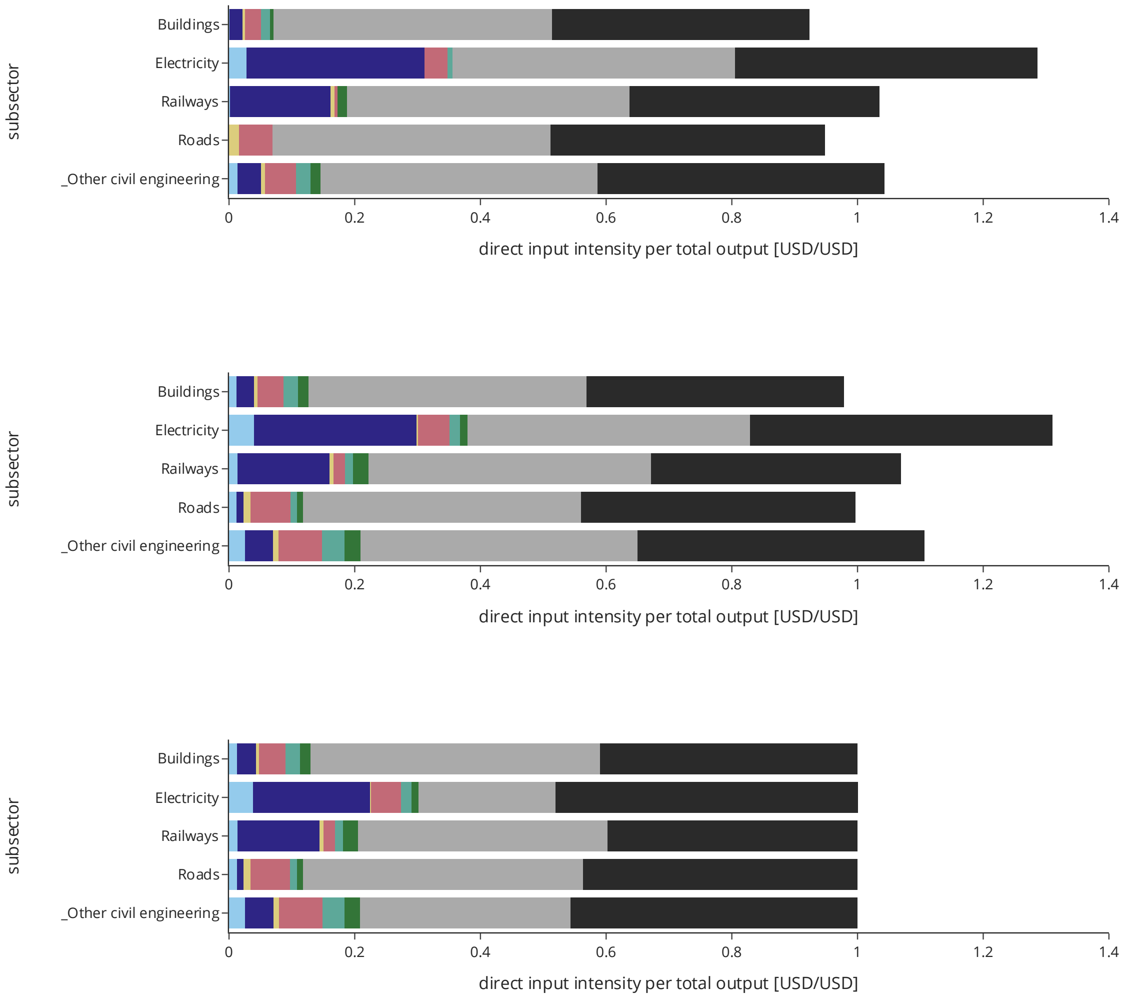


Figure E1: Direct input intensity of EU-27 construction subsectors in 2018: a) based on bottom-up estimate of cost of material input per subsector and top-down accounts of value added, before residual distribution, b) after equal distribution of residuals, c) after balancing inputs and outputs by optimising material prices and other industry inputs.

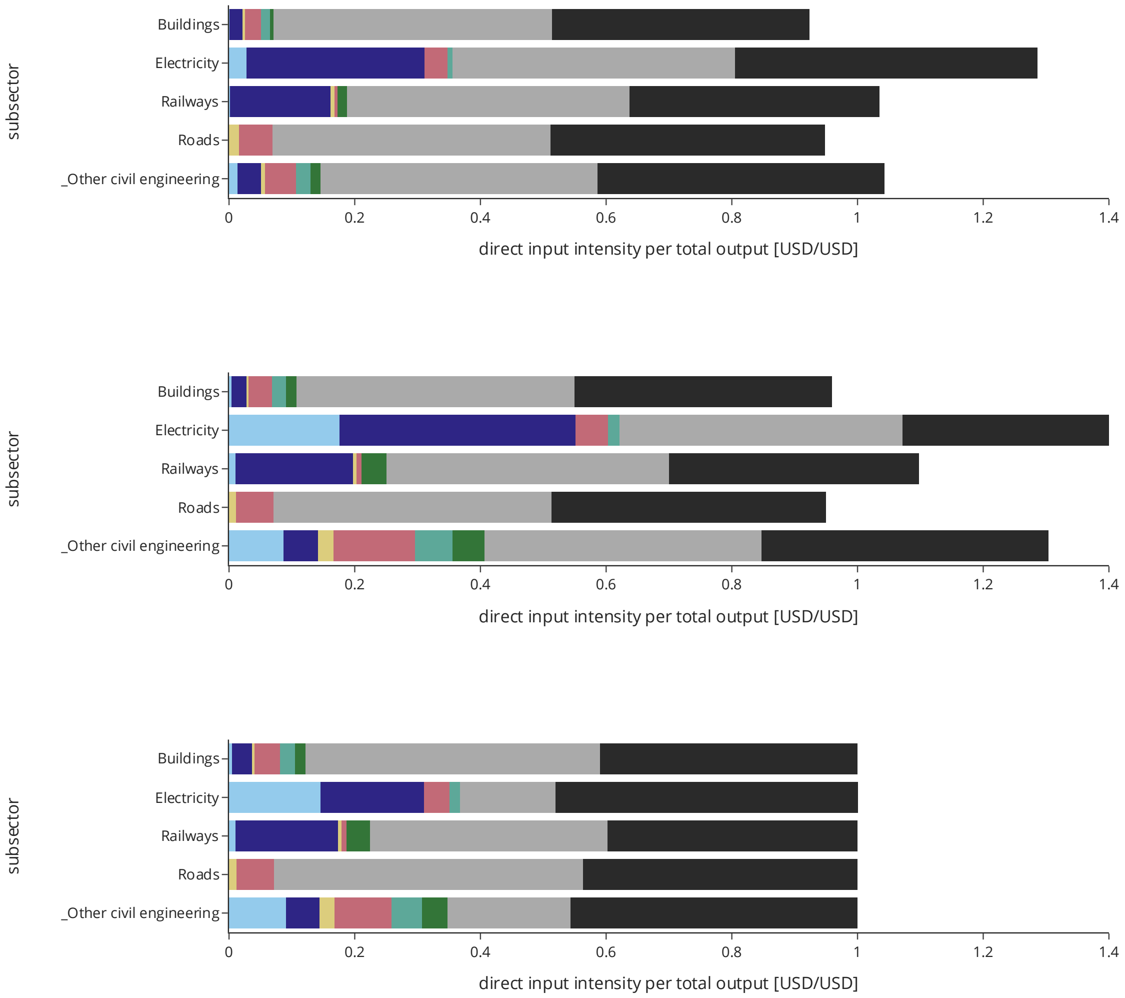


Figure E2: Direct input intensity of EU-27 construction subsectors in 2018: a) based on bottom-up estimate of cost of material input per subsector and top-down accounts of value added, before residual distribution, b) after distribution of residuals according to the share of material inputs indicated by the bottom-up estimate, c) after balancing inputs and outputs by optimising material prices and other industry inputs.

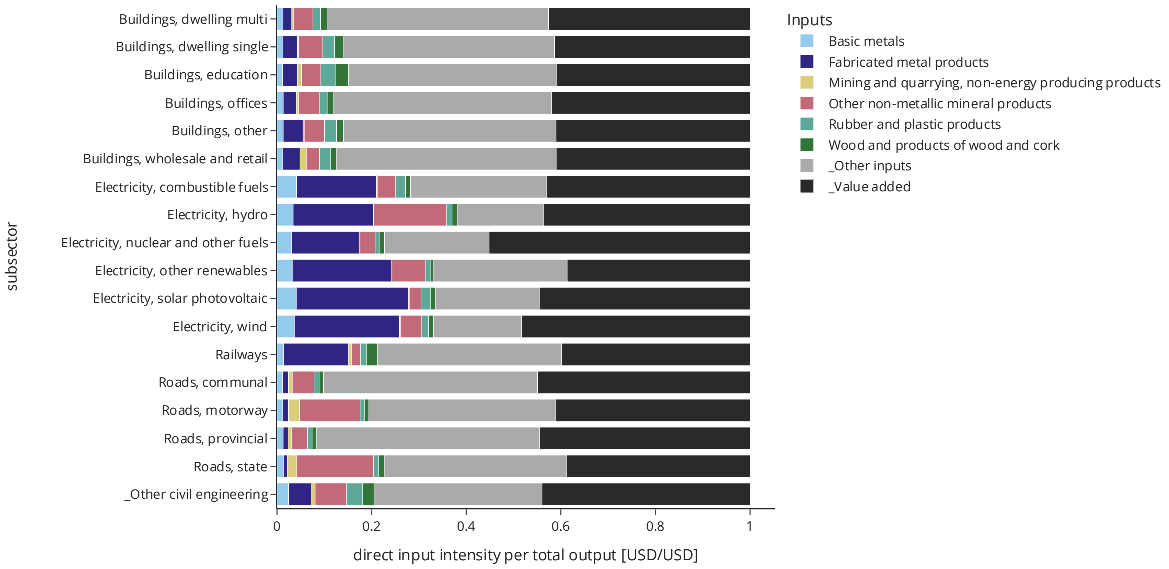


Figure E3: Production technology of each structure in the EU in 2018 under the homogenous price assumption after default distribution of residuals and balancing.

Appendix F: Climate impacts of construction subsectors

This appendix provides additional information on the CO_2 emissions related to EU construction, its subsectors and material inputs. Emissions displayed here generally refer to a footprint perspective, i.e. including direct and indirect upstream emissions of demand. **Figure F1** shows the CO_2 emissions induced per unit spent on construction related to each direct input to construction as reported in ICIO. This suggests that direct material inputs are most responsible for the carbon footprint of construction (while energy use and logistics also bear significant shares). Therefore, the study focussed on collecting bottom-up estimates of material inputs. **Figure F3** shows the EU median carbon multiplier of the material and other inputs depending on the selected background system. This helps to explain the trends visible in **Figure F4** which invigorates the share of which input is particularly decisive for the carbon intensity of a construction subsector in a given country. **Figure F5** then shows the size and composition of the carbon multiplier of each subsector in each EU member state, highlighting differences between the subsectors but also between countries. The accompanying text describes the causes of this cross-country variation. The panel in **Figure F6** compares the cross-country conclusions regarding the carbon intensity of building and road construction depending on whether this is expressed per monetary or per physical unit. The comparison is only made for these two subsectors (not for electricity infrastructure or railway construction) since prices of subsector supply were only relatively constant for buildings and road construction. Variations of the total carbon footprint of construction and its subsector composition at the EU level depending on the underlying bottom-up estimate and modelling assumptions are summarised in **Figure F7**. **Figure F8** shows the distribution of the carbon footprint for each structure assuming homogenous prices of construction supply per square metre (or per generation capacity in the case of electricity infrastructure) within each construction subsector.

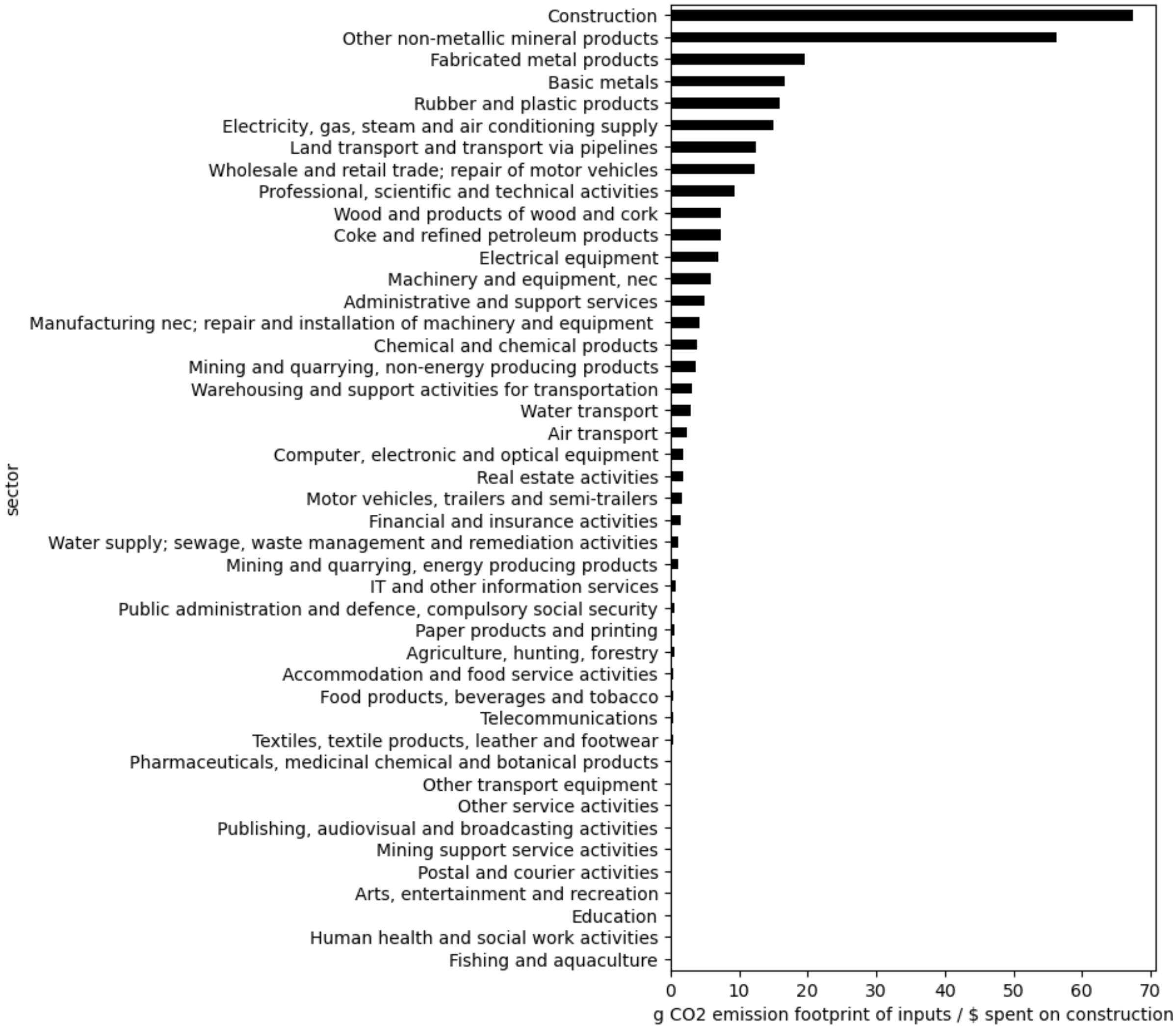


Figure F1: Median carbon multiplier of EU construction by input for the period 2010-2019 as recorded in ICIOv2021.

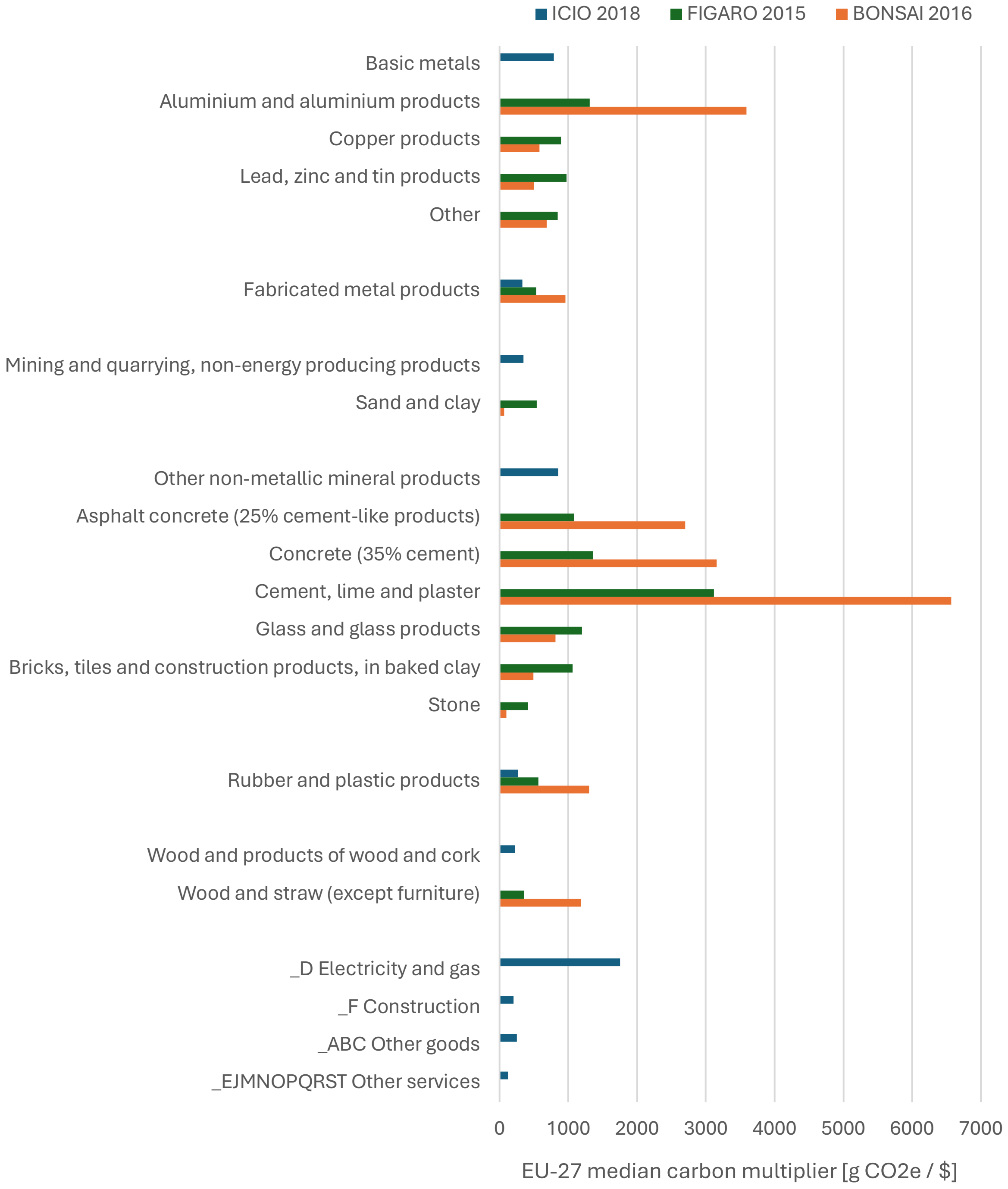


Figure F3: EU-27 median carbon multiplier of the specified material inputs to construction in ICIO, BONSAI and FIGAROe3 database and for the broader input groups (_) in ICIO.

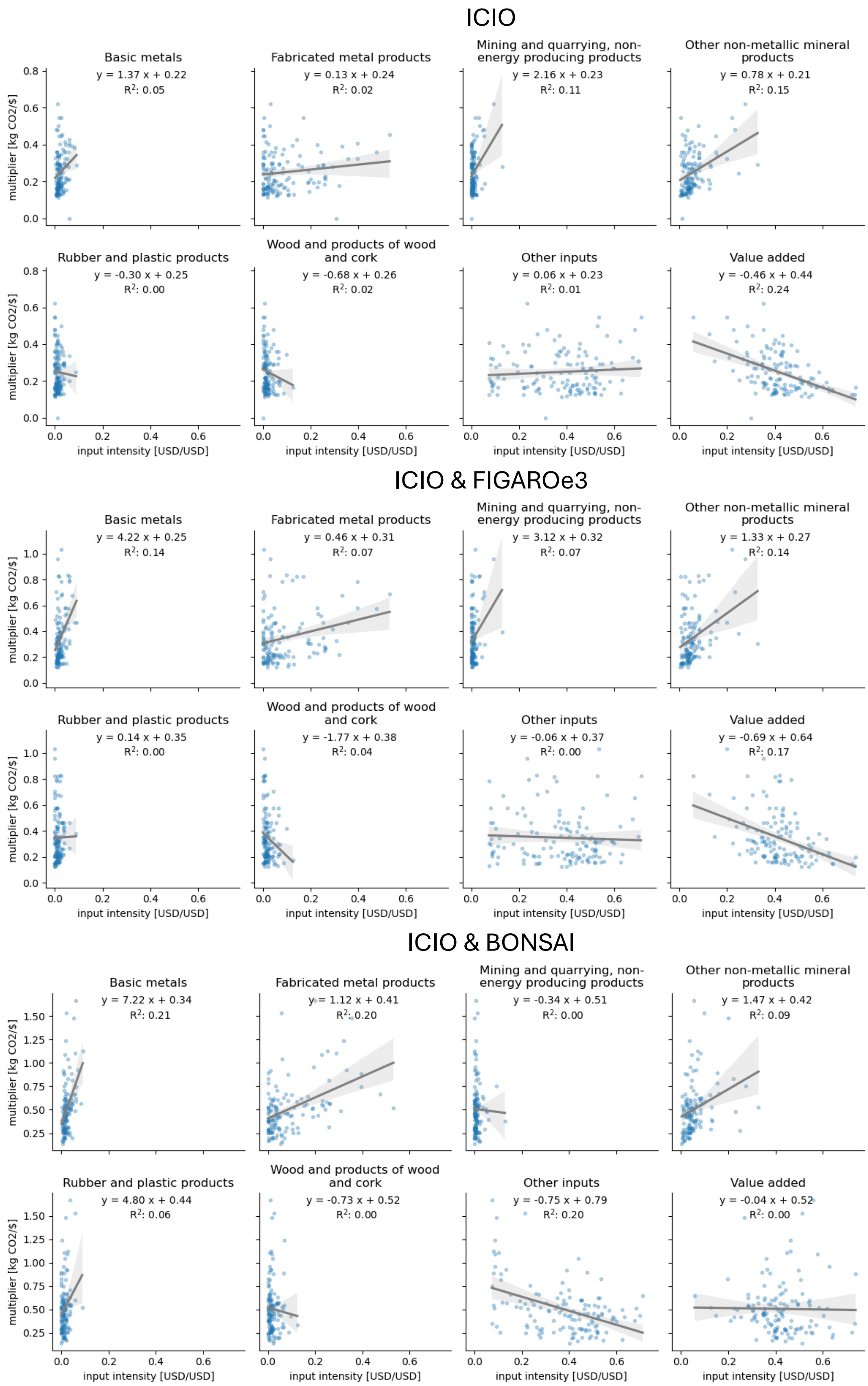


Figure F4: Relationship between the share of an input and carbon multiplier of each country and subsector given material multipliers specified on top. The grey shaded area is the 95% interval of the best fit regression line.

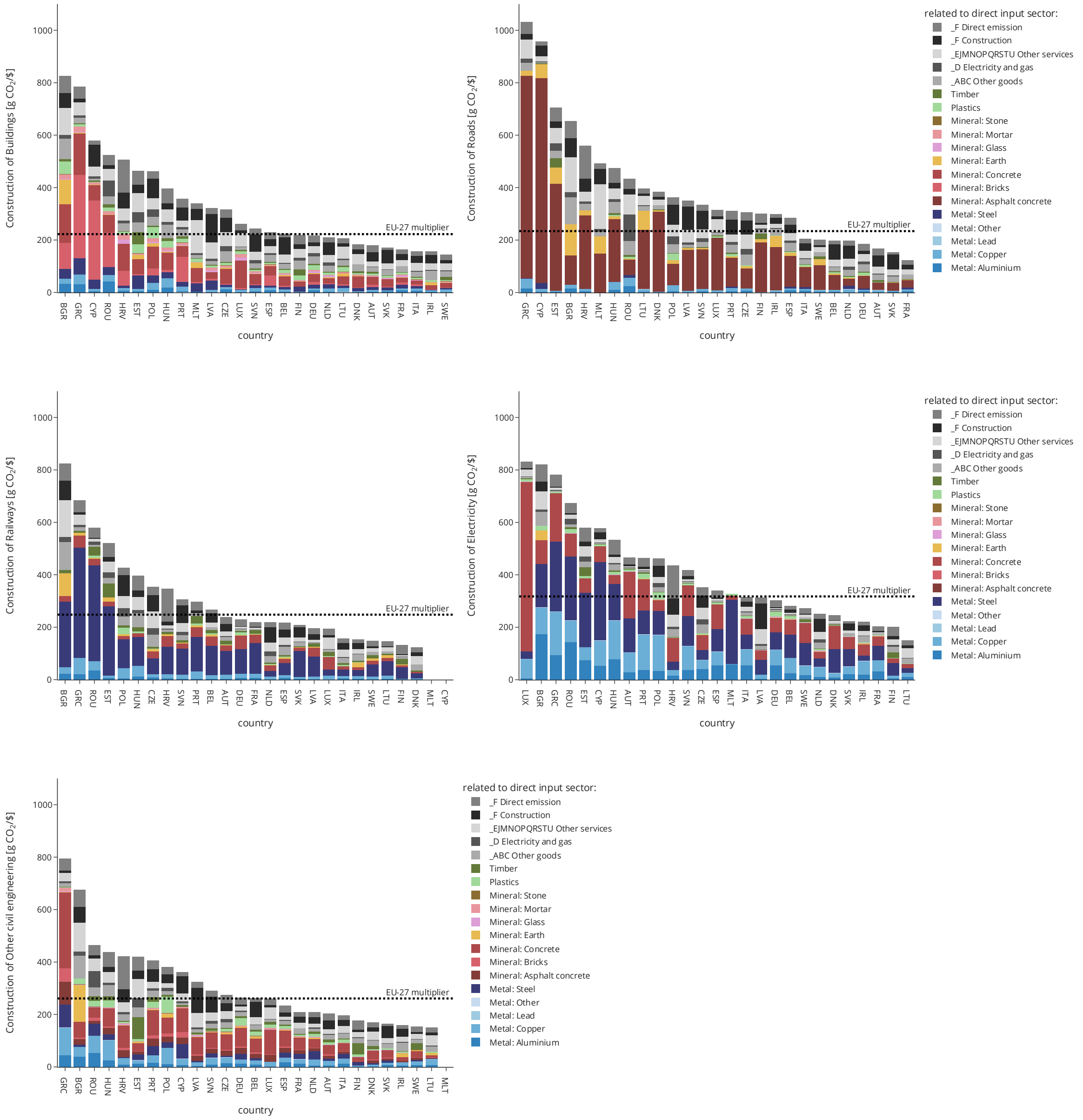


Figure F5: Carbon multipliers of construction in each EU-27 member state in 2018 of buildings (upper left), roads (upper right), railways (middle left), electricity infrastructure (middle right), other civil engineering (bottom). Based on the material-specific approach.

The carbon multiplier of the same subsector varies between countries as a result of the specific structures and material intensities of that country represented in the physical proxies, as well as in the monetary model inputs such as the production technology of the aggregate construction sector or the share of value added in the total output.

Present in the aggregate base MRIOT is that production technology of construction differs between countries. For instance, Finland has a comparably high share of wood in the inputs to aggregate construction, whereas Poland records a lot of plastic inputs and Romania comparatively little other non-metallic minerals.

The physical proxies add that the structure composition and related material intensities of each subsector differ between countries. While at the EU-level the construction and expansion of residential buildings, local roads, and combustible fuels dominated during the 2010s, individual countries strongly differ in the structure composition of the buildings, roads, and electricity infrastructure subsector. For instance, Denmark has a particularly high share of wind power plants in its electricity infrastructure construction volume which results in a high steel intensity that also shows in the multiplier (cf. Appendix Figure C5 and D2). In contrast, concrete plays a larger role in the carbon multiplier of electricity infrastructure in Latvia, Austria and Luxemburg which rely more on hydropower. Similarly, for buildings, the higher share of industrial buildings in Greece, Latvia, and Estland translates into a higher contribution of steel to the carbon multiplier. Nevertheless, the structure composition does not entirely explain differences in the composition and size of the carbon multipliers of subsectors between countries as the carbon intensity of construction materials also differs between countries depending on their sourcing structure.

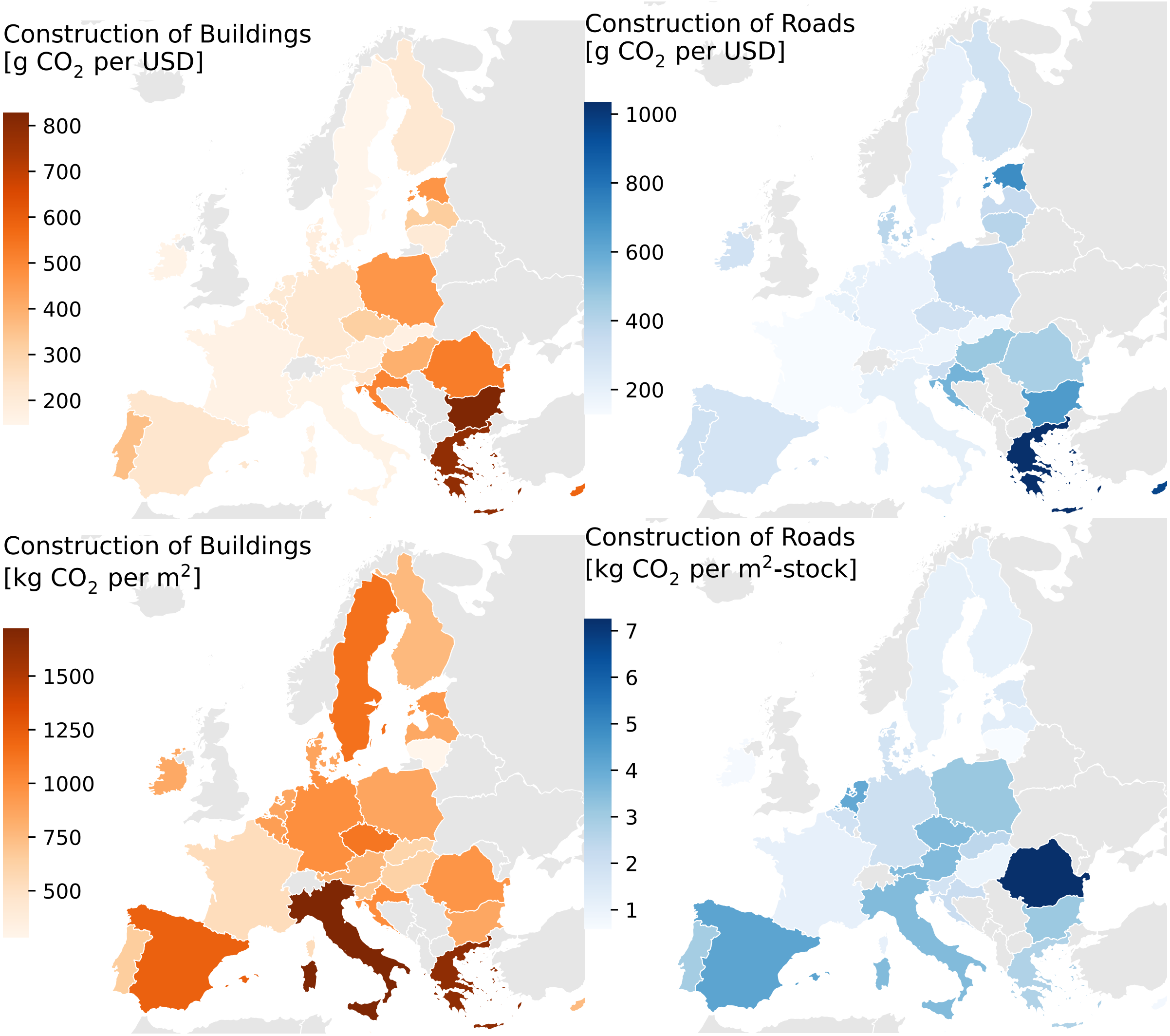


Figure F6: Carbon multiplier of building and road construction: per dollar (upper left and upper right) vs. per square metre of expansion and maintenance of useful floor area for buildings (lower left) and stock for roads (lower right) in EU-27 member states in 2018.

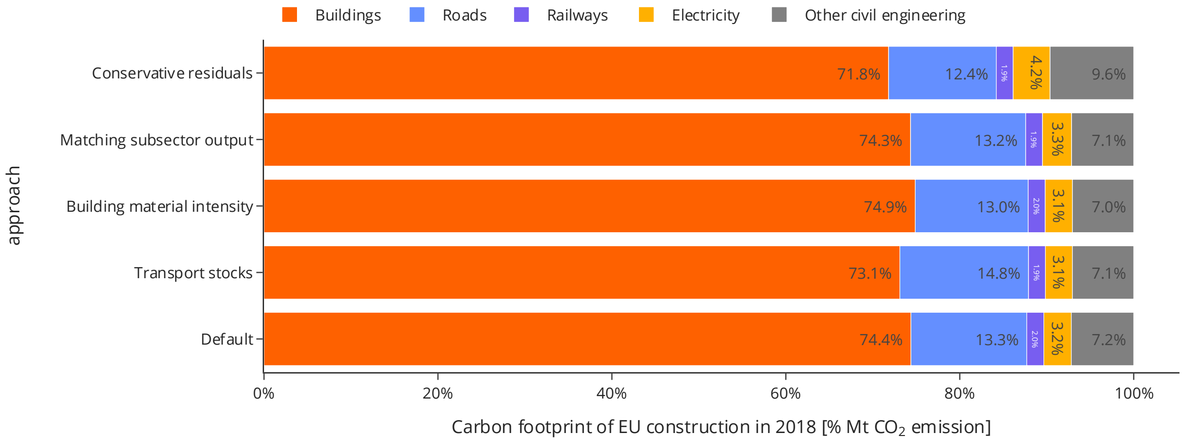


Figure F7: Distribution of the carbon footprint of construction across subsectors in the EU-27. Default: the default procedure suggested in this study using ICIO multipliers for all inputs; Transport Stocks: using road and railway stock estimates specified in Wiedenhofer et al. 2023; Building material intensity: using median building material content intensities specified in Fishman et al. 2024; Matching subsector output: matching intermediate demand for construction with construction subsectors; Conservative residuals: distributing residuals according to the bottom-up estimates rather than equally across subsectors.

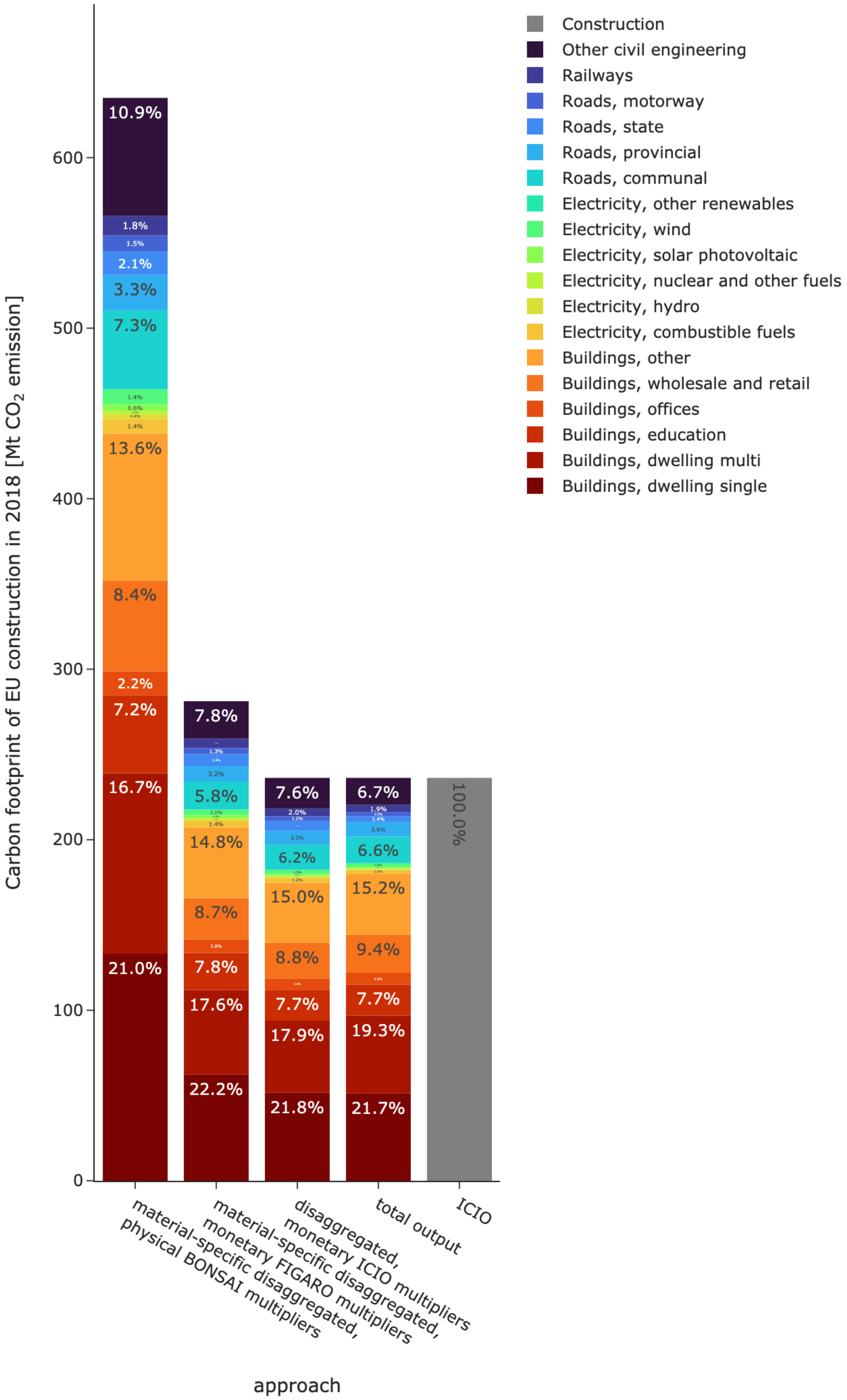


Figure F8: Total CO_2-emission footprint of detailed construction subsectors in the EU-27 in 2018 under the homogenous price assumption.

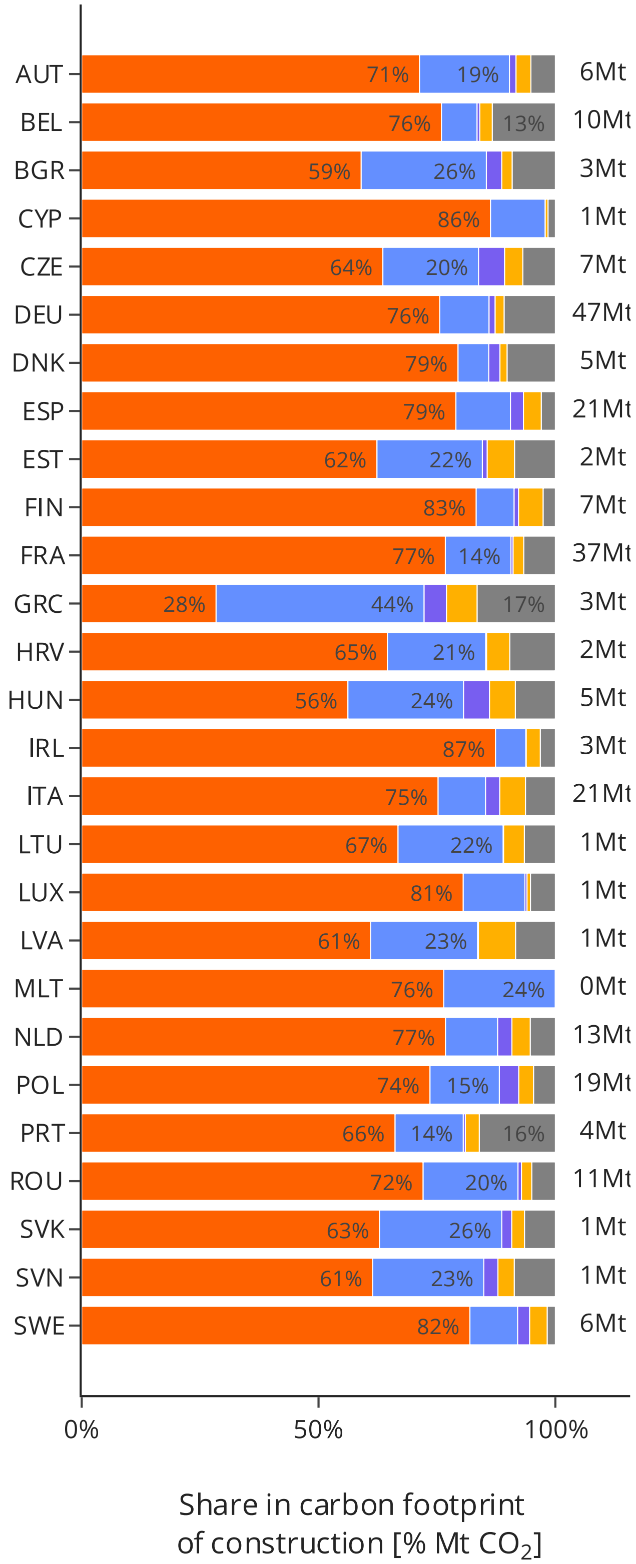


Figure F9: Distribution of the carbon footprint of construction across subsectors of each EU country in 2018. Based on the endogenous disaggregated ICIO approach.