TRANSIENCE

TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

Date: 26/05/2025

D4.3 – EU material and sectoral flow pilot modules

WP4 – Developing satellite modules

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Responsible Author	Mathieu Saurat		**Email**	mathieu.saurat@wupperinst.org
	WI		**Phone**	+49 202 2492-132
Contributors	Meta Thurid Lotz (Fraunhofer); Simon Lukas Bussmann (Fraunhofer)			
Reviewer(s)	Konstantinos Koasidis, Alexandros Nikas (ICCS); Jakob Dürrwächter (PIK); Li Shen (UU); Teresa Domenech (UCL)			
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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This document, Deliverable D4.3 of the TRANSIENCE project, is intended for the broader stakeholder community as well as particularly energy-system and climate-economy modelling teams. It provides an overview of the material and sectoral flow pilot modules developed in the context of this project, including their planned integration into the Model for European Industry Circularity and Climate Change Mitigation (MIC3). As such, this document and the developed modules constitute a critical element to achieve an integrated modelling framework for the European industry, i.e. MIC3. Modelling practitioners may use these modules as standalone or in combination with the other satellite modules developed within TRANSIENCE to inform decision-makers on diverse pathways toward a material-efficient, circular, climate-neutral, sustainable European industry.

3. Short summary of results (<250 words)

This document presents an overview of the developed material and sectoral flow pilot modules for the EU (EU MFA). It describes the concept, data inputs and outputs, and novelty of underlying modules, as well as their planned integration into the Model for European Industry Circularity and Climate Change Mitigation (MIC3), coupled with exemplary results. The developed material and sectoral flow pilot modules translate demand for selected products (e.g., buildings, vehicles) in demand for selected materials (i.e., steel, plastics, cement). In contrast to existing approaches, the modules allow the combination of bottom-up and top-down approaches to utilise their specific advantages. Within the MIC3 framework, the developed material and sectoral flow modules will receive inputs from the computable general equilibrium, energy-system, and global material flow modules, towards providing inputs to the technoeconomic industry modules. The exemplary results included in this report present a baseline scenario extending historical trends, which partly contains placeholder data, where input from other modules will be integrated in the second phase of the project.

4. Evidence of accomplishment

The GitHub repository including a preliminary documentation and this report.

Preface

The need to approach climate action, resource efficiency, and circularity performance as integrated, economy-wide, cross-cutting issues is growingly gaining attention in the policy world, stimulating the development of new industrial policies in Europe and worldwide. Currently, however, there is little progress in conceptualising the circular economy and understanding its interactions with climate action. State-of-the-art modelling capacity to capture the interplay of the two agendas and their implications for energy-intensive sectors as well as to represent the European industry's transformation in line with the region's vision for climate neutrality is not yet fully developed. TRANSIENCE will undertake a comprehensive characterisation and assessment of circularity principles and measures vis-à-vis decarbonisation, by looking at the twin transition of European industries through the lenses of global competitiveness, innovation, and holistic sustainability. It will then produce MIC3, a consistent, fully open-source model ecosystem to assess industrial circularity, decarbonisation, and sustainability. A series of interoperable modules on the socioeconomic, service and product, material, industrial, energy-system, and environmental perspectives of the transformation of European industry will be developed and integrated, building on and opening the code of leading modelling tools. MIC3 will finally be used in extensive scenario modelling to produce diverse pathways toward a material-efficient, circular, climate-neutral, sustainable European industry. Transparency, openness, and knowledge sharing will be promoted, and technical capacities will be developed in four industrial agglomerations in the EU, moving beyond stakeholder consultation, onto model co-development, continuous validation of assumptions, co-creation of scenario modelling, evaluation of the desirability and usability of the developed model and insights, and eventually co-production of science and action.

ICCS – Institute of Communication and Computer Systems	EL
CEPS – Centre for European Policy Studies	BE
E3M – E3-Modelling AE	EL
Fraunhofer – Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	DE
HOL – HOLISTIC IKE	EL
PIK – Potsdam Institut für Klimafolgenforschung e.V.	DE
PNTEC – Park Naukowo-Technologiczny Euro-Centrum Spolka Z Ograniczona Odpowiedzialnoscia	PL
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Executive Summary

This document provides an overview of the material and sectoral flow modules for the European Union (EU), hereinafter referred to as EU MFA. The EU MFA module is a multi-regional dynamic Material Flow Analysis (MFA) of the basic materials steel, plastics, and cement. The EU MFA module is a central module within the planned Model for European Industry Circularity and Climate Change Mitigation (MIC3). It translates products into material demand and thereby links macroeconomic developments with the basic industry. Within the MIC3 framework, the developed material and sectoral flow sub-modules will receive input from the computable general equilibrium (CGE), the energy system and the global MFA modules. The developed EU MFA sub-modules will in turn provide input into the technoeconomic industry modules. Moreover, the EU MFA plays a key role within MIC3, in terms of assessing circular economy measures. In contrast to existing approaches, the sub-modules allow the combination of bottom-up and top-down approaches to utilise their specific advantages (i.e., full coverage of end-use sectors vs. high level of detail for modelling a circular economy). Further developments of the sub-modules are planned to integrate circular economy elements and automatise visualisation and documentation as well as harmonisation for linking with other MIC3 modules. The exemplary results included in this report present a baseline scenario extending historical trends, which partly contains placeholder data.

Code metadata	
Current code version	v.0.1
Link to code repository	https://github.com/wupperinst/transience-eu-mfa/
Legal Code License	Open-source license (see repository)
Code versioning system used	git
Software code language	Python
Particular tools, services, modules used	flodym module https://github.com/pik-piam/flodym
Compilation requirements, operating environments & dependencies	Tested with Python 3.9 and the modules listed in the requirements.txt file
Link to documentation / manual	https://transience-eu-mfa.readthedocs.io/en/latest/

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1 Introduction

This document provides an overview of the material and sectoral flow module for the European Union (EU), or *EU MFA*, provided as a GitHub repository including preliminary documentation, which will be further developed and finalised in the second phase of the project[1]. The EU MFA is a multi-regional dynamic Material Flow Analysis (MFA) resulting in material production and waste generation of the basic materials steel, plastics, and cement (see also Section 2.2.2 for more detailed information on module outputs). As shown in **Figure 1**, the EU MFA is a central module within the planned Model for European Industry Circularity and Climate Change Mitigation (MIC3). As described in deliverable D3.4 (*'Framework for industry transition modelling'*), it translates macroeconomic development into material demand for production in the basic industries. Consequently, the EU MFA module receives inputs from the computable general equilibrium (CGE) module, the global MFA module, and the energy system module. The product and service (P&S) database has a crucial function in translating socioeconomic indicators into product demand. The EU MFA module provides output for the technoeconomic industry modules. Moreover, it plays a key role within MIC3 for assessing circular economy (CE) measures, which are described in detail in previous project deliverables[2]. This document focusses on the brief documentation of the development of the sub-modules within the EU material and sectoral flow module as well as their linkages to other modules in the MIC3 framework.

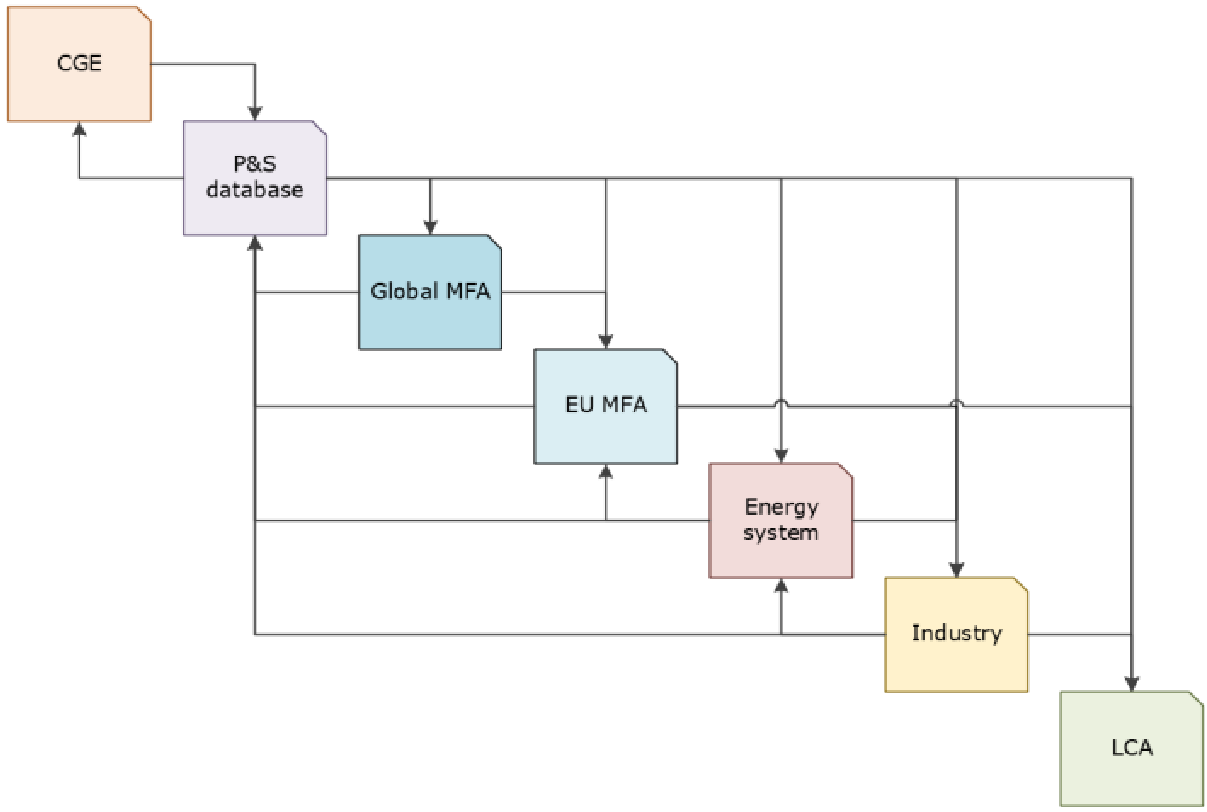

Figure 1. Planned interfaces in the MIC3 baseline workflow

[1] https://github.com/wupperinst/transience-eu-mfa
[2] D3.2 – Open model development strategy, D3.3 – Conceptualisation of CE and policy mapping, D3.4 – Framework for industry transition modelling

2 Module description

The EU MFA is built as a sequence of processes connected by flows of the basic materials steel, plastics, and cement (Section 2.1). The activities in each process and flow are driven by exogenous parameters such as consumption levels, product lifetimes, trade, and waste collection rates, which are set in line with the respective scenario definition (Section 2.2). The EU MFA is developed in python, built on the flodym (Flexible Open Dynamic Material Systems Model) library, developed within the TRANSIENCE project (Task 4.5). Developing all sub-modules of the EU MFA with the flodym framework ensures a consistent code base within the module as well as with the Global MFA module (part of MIC3)—which is also built with flodym.

2.1 Concept

The EU MFA module is an implementation of the dynamic MFA method (Deng, Zhang, & Fu, 2023), which is represented in a process material flow diagram in **Figure 2**. With the objective of analysing the impact of a circular economy in the context of industry decarbonisation, the MFA assesses the three emission-intensive basic materials, namely steel, plastics, and cement, as well as their end use sectors. In general, the future development of material production volumes and secondary material availability are driven by the use phase (and trade) (Lauinger, Billy, Vásquez, & Müller, 2021).

The EU MFA module incorporates a diverse range of product types across the end use sectors, spanning from composite products (e.g., vehicles), to mono-material components that form part of composite products (e.g., moulded polyurethane seats in vehicles or PVC profiles in buildings), and mono-material stand-alone products (e.g., plastic packaging, toys, or agriculture foils). For this purpose, the MFA module can combine five sub-modules to ensure coverage of all end-use sectors and detailed analysis of particularly relevant sub-sectors:

1. Bottom-up stock-driven approach for buildings driven by the stock development
2. Bottom-up inflow-driven approach for vehicles driven by new passenger car registrations
3. Top-down inflow-driven approach for steel driven by consumption changes of 19 steel products in construction, automotive, other transport, mechanical engineering, metalware, domestic appliances, and miscellaneous
4. Top-down inflow-driven approach for plastics driven by consumption changes of 14 polymer types in building & construction, automotive, packaging, electrical & electronics, agriculture, household/leisure/sport, and others
5. Top-down inflow-driven approach for cement driven by consumption changes in buildings and infrastructure

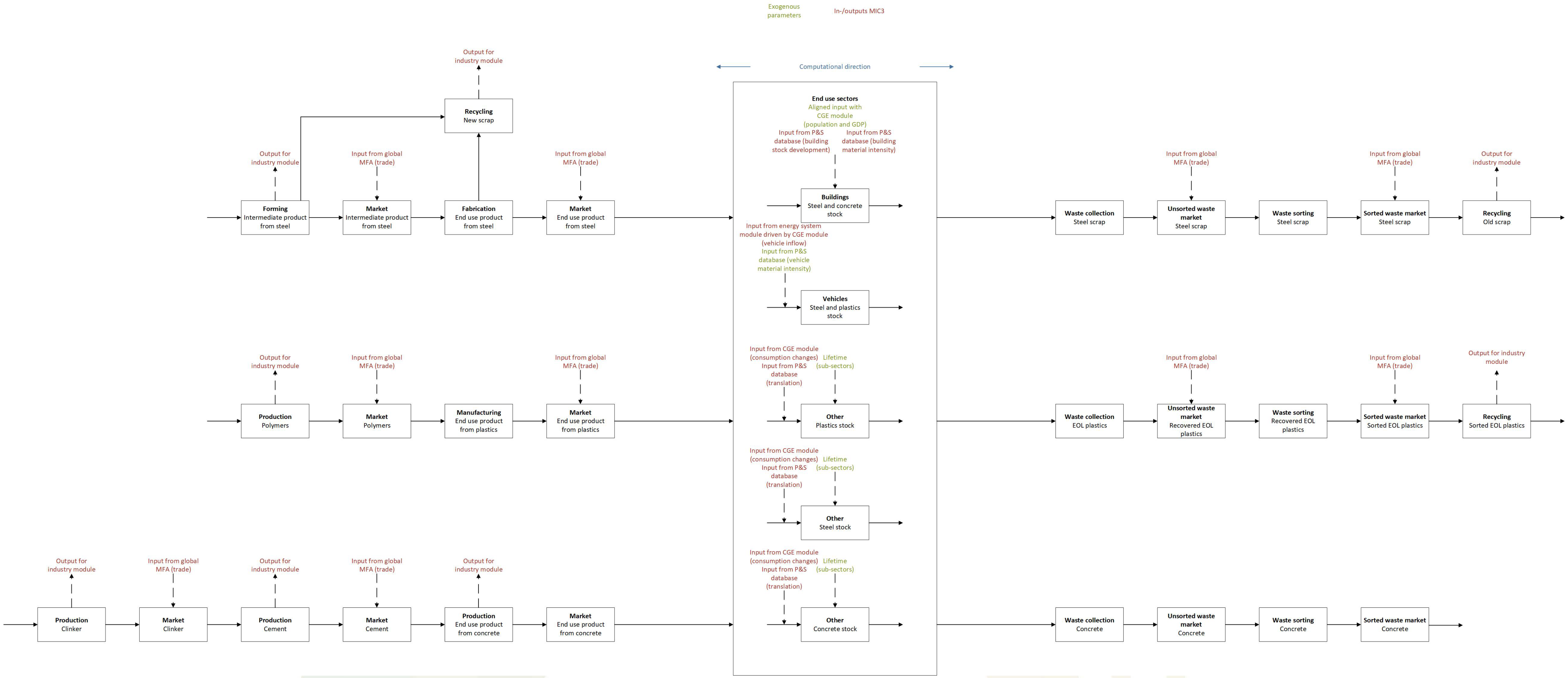

Figure 2. Diagram for the EU MFA module, based on Bergsdal, Brattebø, Bohne, and Müller (2007)

In this context, a particular challenge arises from the differentiation between broad application sectors (e.g., Automotive, Buildings & Construction, Packaging, Electrical & Electronics Equipment, Agriculture, etc.) and detailed application sectors that are parts of the broad ones (e.g., "vehicles" as part of "Automotive", "Residential buildings" as part of "Buildings & Construction") (Villalba, Iglesias, & Gabarrell, 2018)—see also **Figure 3**.

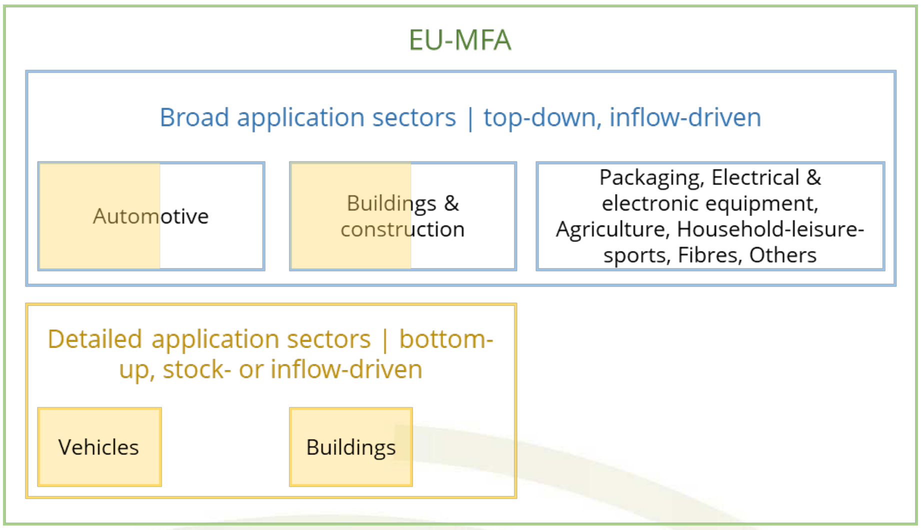

Figure 3. Product and sectoral resolution of the EU MFA

To ensure consistency between the sub-modules and to account for the varying differentiation between broad and detailed application sectors, the EU MFA module relies on statistical data for a base year. In detail, we use a somewhat different inflow-driven approach to that used for modelling scenarios. The reason is data availability for basic material demand: It is readily available for the "Production" process in the module's material flow diagram. Adding net trade to "Production" yields final demand, which in turn is the driver-variable that is modified when building scenarios. In general, the bottom-up material flows for the detailed application sectors are subtracted from top-down flows for the respective broad application sector. The residual ("Other") is then extrapolated. Rates of change in consumption, delivered from the CGE module, as well as translation factors, from the P&S database, will provide the basis for these modifications. Therefore, in scenarios, "Production" is a model output, while final demand is an input parameter. This approach necessitates a reference development when circular economy measures are considered. The circular economy measures affect the top-down and bottom-up inflows independently of each other.

2.2 Data

2.2.1 Inputs

The EU MFA requires a broad range of input data, which are partly derived from other MIC3 modules. The following table (**Table 1**) presents an aggregated list of exogenous parameters and their source. More details on the sources for exogenous parameters not derived from other MIC3 modules can be found in the Annex.

Table 1. Exogenous parameters

Parameter	Description	Source
Material intensity of buildings and vehicles	Determines the use of materials per unit	P&S database
Building in- and outflows	Determines the construction and demolition of buildings	P&S database
Vehicle registrations	Determines number of new vehicles	OpenPROM
Consumption change	Indicates changes in the consumption changes in monetary units	OpenGEM
Translation	Indicates changes in the relationship between monetary and physical units	P&S database
Lifetimes	Indicates lifetime of products per use sector (mean and standard deviation)	Literature
Intra-EU trade	Determines exports and imports of basic materials, intermediaries, final products and waste	Various sources, harmonised with OpenGEM
Extra-EU trade		Global MFA
Production	Determines basic material production	Statistics
Process characteristics	Determines losses or input factors for specific processes	Literature
End use matrix	Allocates demand to end use sectors	Literature/ statistics

2.2.2 Outputs

The EU MFA generates a broad set of results. The table below presents the two main output variables, which are used by the technoeconomic industry modules. Section 4 presents some exemplary results.

Table 2. Outputs to other modules (preliminary)

Parameter	Description	Sink
Production	Production of basic materials	Technoeconomic industry module
Waste/scrap	Availability of waste and scrap for secondary production	Technoeconomic industry module

3 Novelty and next steps

The core novelty of the EU MFA module lies in the integration of bottom-up and top-down approaches to utilise their specific advantages (i.e., full coverage of end-use sectors vs. high level of detail for modelling a circular economy). This integration goes beyond the soft-linkage of modules, and the resulting MFA enables the coverage of all end-uses (not only selected ones) of the most energy-intensive materials (i.e., steel, plastics, and cement). Buildings and vehicles are selected products, which are covered in high detail due to their relevance in the context of a circular economy. At the current stage, this integration was implemented and tested for one use case example (described below) to present one added value of the module and will be rolled out to the other materials in the course of the TRANSIENCE project.

Moreover, the five sub-modules of the EU MFA were improved, two of which were originally developed before the TRANSIENCE project:

- The multiregional top-down MFA for polymers was made open. Extending a previously published version[3], the module includes an alternative computational logic that is in line with the requirements of MIC3: demand-driven MFA (in addition to production-driven). The adapted computational logic allows linkage with the bottom-up approaches. The existing code was entirely refactored using the modelling framework flodym, which is an adaptation of the ODYM framework. Moreover, the model was enhanced with the possibility to focus on specific products at a detailed level, if a research question requires it. This approach extends to the EU-27 member states, according to the work by Domenech et al. (2021), who associated coefficients on plastic content and polymer composition for over 600 products from Eurostat's "Sold production, exports and imports by PRODCOM list (NACE Rev. 2)" for the UK.
- The bottom-up stock-driven MFA of steel and concrete/cement for buildings was made open (Lotz et al., 2024). The initial version covering buildings was published in 2022 as part of the H2020-project newTRENDs[4]. The sub-module was improved by including various polymer-based insulation products, which enables the linkage with the top-down MFA of polymers described above. Moreover, the granularity of concrete products was increased to establish a new linkage with one of the technoeconomic industry modules. Also, the code was adapted to the model framework flodym.
- A new top-down inflow-driven MFA was developed for cement to cover another key demand sector for concrete/cement in addition to buildings, namely infrastructure. This newly developed module, in combination with the bottom-up MFA of buildings, serves as a case example for the integration of bottom-up and top-down approaches within the EU MFA pilot (see Section 4.1). In contrast to the soft linking of the existing bottom-up MFA

[3] https://bitbucket.org/wupperinst/edm-stock_plastics_greenfeed/src/master/

[4] https://github.com/H2020-newTRENDs/flow

with one of the technoeconomic industry modules (Lotz et al., 2025), this integration requires fewer assumptions and provides a more consistent depiction of future material flows.

- A new top-down inflow-driven European steel MFA has been developed as open-source. It covers all steel demand in seven broad use sectors and about twenty steel products (sub-categories of cast, flat, long, and tube products). This combination is, to our knowledge, a unique feature of the model. Indeed, steel scrap presents widely different levels of copper contamination depending on the sector from which it is collected. At the same time, each of the steel product considered has a specific copper tolerance range. Both aspects are tracked in the MFA and passed onto the industry module where they play a key role in the optimisation (see Section 4.2 for more details).
- A new bottom-up approach for steel and polymer-based products in passenger cars was developed based on the flodym framework. In contrast to the other sub-modules described above, this module is driven by the energy system module and not the CGE one. It follows the same differentiation of materials as the top-down approaches for polymers and steel, enabling the integration of approaches.

Next steps for the second phase of the project include roll-out of the integration between the top-down and bottom-up approaches, harmonisation between EU MFA and other modules in MIC3 (especially, but not restricted to, the global MFA module), automated visualisations, and complete documentation.

Beyond these technical aspects, the second phase of the project focusses upon the modelling of case studies for decarbonisation and circularity. For this purpose, we mapped exemplary circular economy elements from Deliverable D3.5 (*'Open database of policies & technologies'*) for each MFA sub-module, including a short description of the planned module implementation in **Table 3**.

Table 3. Exemplary circular economy elements and their planned module implementation

Circular economy element	Sub-module	Planned implementation
Reducing floor space demand	Buildings	Adapting the input from the P&S database on the building stock development
Timber instead of concrete	Buildings	Adapting the input from the P&S database on the building material intensities
Reuse of original concrete slabs for new buildings	Buildings	Introducing a new reuse flow for building elements
Lightweighting of vehicles/ vehicle metal parts	Vehicles	Adapting the input from the P&S database on the vehicle material intensities
Reuse of steel components/ metal parts in cars	Vehicles	Introducing a new reuse flow for vehicle components

Circular economy element	Sub-module	Planned implementation
Reduce - More durable product design	Plastics, Steel	Introducing lifetime parameters varying with time (e.g. extending mean lifetime from a given year, see below)
Repair - Maintain the functionality of a product	Plastics, Steel	Introducing lifetime parameters varying with age-cohort (see below)
Refuse - Avoid the production or consumption of a specific product	Plastics	Introducing ad-hoc detailed, PRODCOM-based product level
Reuse of cast-in-place for infrastructure projects	Cement	Introducing a new reuse flow for cement in infrastructure

Lifetime parameters of products are central in stock dynamic MFA models. These are usually implemented as probability distributions, which are translated at runtime into survival functions *sf(m,n)*, which represent the share of an inflow in year *n* (age-cohort *n*) still present at the end of year *m* (after *m-n* years). We have implemented the possibility to let lifetime parameters vary with time and/or age-cohort in the top-down sub-modules. This allows for modelling the introduction of circularity strategies such as built-to-last and right-to-repair types of measures.

The graph in **Figure 4** exemplifies the effect of time or age-cohort dependent lifetimes for some fictitious product in a fictitious use sector. It shows the lifetime normal probability distributions (left) before and after the introduction of some circularity measure in 2020 (resulting in longer mean lifetime) and the corresponding survival functions for the age-cohorts 2010, 2019 and 2021 (right):

- Lifetime_c: the probability distribution for an imaginary product change from 2020 onwards for NEW cohorts. Cohorts 2010 and 2019 have the same sf but the average lifetime is much longer for cohort 2021.
- Lifetime_t: the probability distribution for an imaginary product change from 2020 onwards for ALL cohorts. Cohort 2019 has in 2019 the same sf as the cohort 2010 in 2010 but in 2020 the sf of cohort 2019 changes and follows that defined from year 2020 (with a higher mean lifetime).

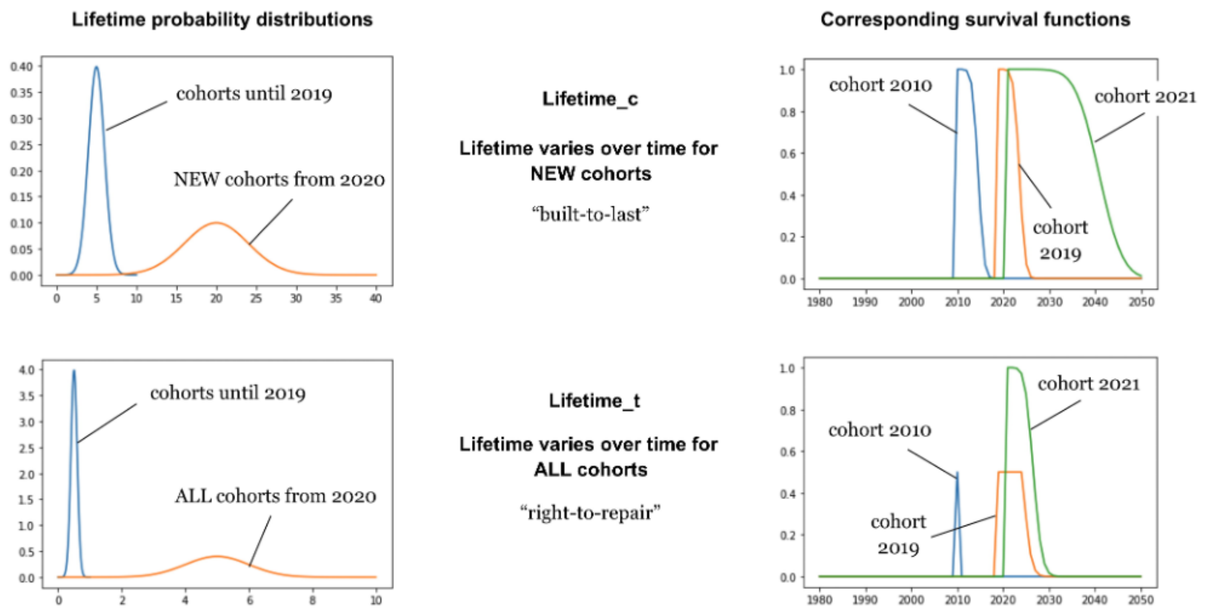

Figure 4. Survival functions from normally distributed lifetimes that can vary with either time or age-cohort

4 Exemplary results

As mentioned in Section 1, EU MFA is a key module within MIC3 for assessing CE measures. Within this section, we present two examples for results that highlight this:

1. Comparison of results of the top-down cement MFA and the integrated cement MFA showcasing the advantages, i.e., full coverage and high level of detail.
2. Results for the production and secondary material of the top-down steel MFA and their integration into the technoeconomic industry module.

4.1 Comparison of top-down and integrated results for cement

The integration of a top-down MFA for cement and a bottom-up stock-driven MFA for cement in buildings is an example of the core novelty of the EU MFA developed within TRANSIENCE. As described above, the top-down and bottom-up inflows are extrapolated independently of each other. The resulting difference between the results for the concrete demand in a solely top-down MFA and the integrated MFA are presented in **Figure 5**.

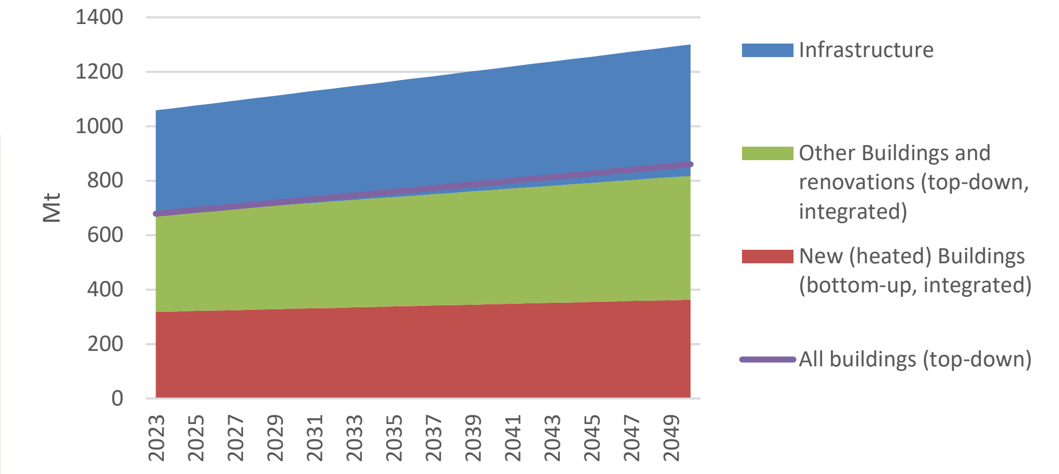

Figure 5. Comparison of the results for the top-down and integrated MFA for concrete demand[5]

As expected, the end use "Infrastructure" is not affected by the integration of the bottom-up MFA for buildings. In contrast, the results for "All buildings (top-down)" as well as the total of "Other buildings and renovations (top-down, integrated)" and "New (heated) buildings (bottom-up, integrated)" differ. While the former is driven by one growth rate, the latter is determined by the same growth rate and the building stock development. Note that dummy data are used for the growth rate and trade, which will be later replaced by data from the CGE module, the P&S database, and the global MFA module. As expected, only a portion of the concrete demand for buildings is covered by the bottom-up MFA. The MFA focusses on concrete demand for new (heated) buildings excluding renovations. However, it is impossible to fully explain top-down material demand through bottom-up product archetypes without additional assumptions.

[5] Please note that dummy data are considered for the growth rate and trade in the top-down MFA

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Nonetheless, this integration is key for the modelling of CE measures in the course of the TRANSIENCE project. While the top-down approach allows the coverage of all end use sectors and thus depicts the total material demand and available secondary material, the bottom-up approach for buildings allows to assess a high level of detail (including eight building types in three climate regions consisting of 36 concrete products—e.g., exterior wall from reinforced transport concrete or roof from not reinforced precast concrete). This enables analysis of specific CE measures mentioned in D3.5 (*'Open database of policies & technologies'*), for instance decreasing floor space in residential and office buildings, material-efficient design of buildings or reuse of building components (Lotz, Rosales Carreón, et al., 2024).

4.2 Results for steel and their integration into industry module

Production of finished steel products and steel scrap generation are two central variables of the top-down steel sub-module (see Section 2.2.2). Both are fed as exogenous model parameters into the industry module's sub-module ITOM (Industry Transformation Optimization Model). The production volumes prior to 2020 are calibrated using industry association data (EUROFER, World Steel). This step (not detailed here) is quite convoluted and requires auxiliary data and assumptions because none of the industry data sources features the required sectoral and product resolutions at the same time. The results presented here rely on preliminary assumptions, particularly regarding trends for future demand, which will be derived from the socioeconomic module in the second phase of the project.

Figure 6 shows the timeseries of finished steel production by use applications (left) and steel product (right) generated with the steel sub-module. The underlying product distribution by sector of application is shown in **Figure 7** for the year 2020. In ITOM, different finished steel products have different copper contamination tolerances. **Figure 8** shows the tolerance ranges by product (these are the widest ranges, for given applications the tolerances may be stricter).

Figure 9 shows the timeseries of scrap availability for the European steel industry as it comes out of the sub-module stock dynamics model. Depending on the steel product and sector of application, the scrap collection and sorting processes result in different levels of copper contaminations. Not all steel scrap is therefore equal. The figure also shows copper contamination levels modelled in the sub-module, which, when passed onto the industry module, is a key piece of information on scrap quality and how it is suited for secondary steel production.

The ITOM steel model, receiving the production and scrap data presented above, then optimises scrap use to meet finished steel production. The model also optimises investments in production technologies (different primary and secondary production routes). By matching the copper concentration of steel scrap with the copper tolerance range of each finished steel product, the model optimises scrap use in the secondary routes both from an economic perspective and from a technical perspective, ensuring that the quality standards of all finished steel products are met.

It should be noted that the steel sub-module only considers copper contamination, as does the industry module ITOM steel. Other contaminants or alloys such as nickel and chromium, which also play an important role in scrap classification, are not considered. Copper contamination alone significantly constraints the optimisation of scrap use in ITOM (as described above) and delivers the desired modelling effect.

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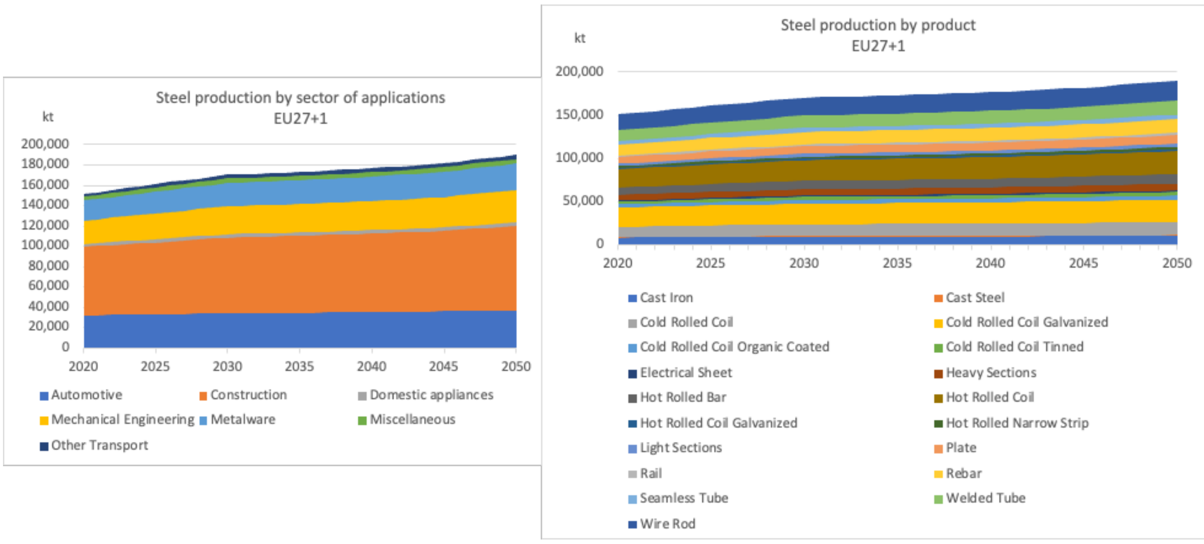

Figure 6. Baseline steel production scenario in EU-MFA steel sub-module, by sector of applications (left) and by product (right), for the EU27+1, 2020-2050

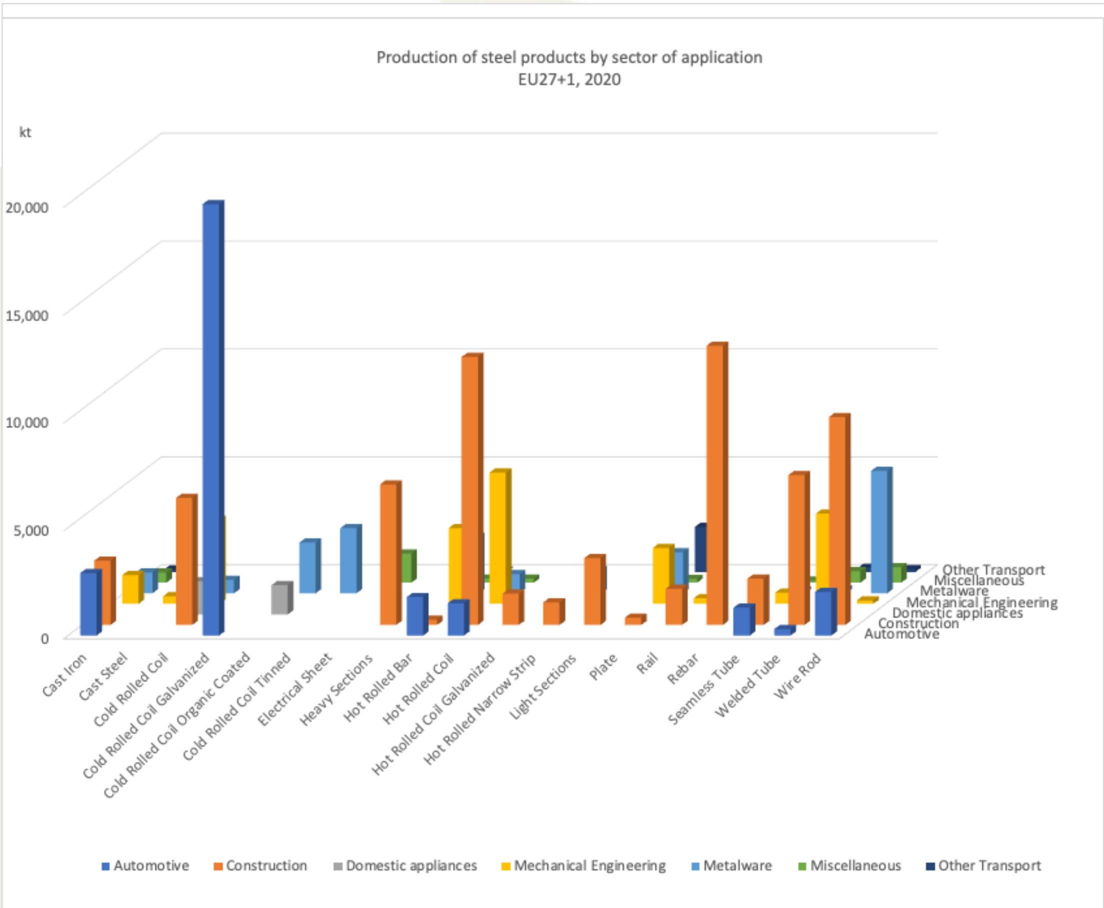

Figure 7. Baseline distribution of steel production by product and sector of application in EU-MFA steel sub-module (EU27+1, 2020)

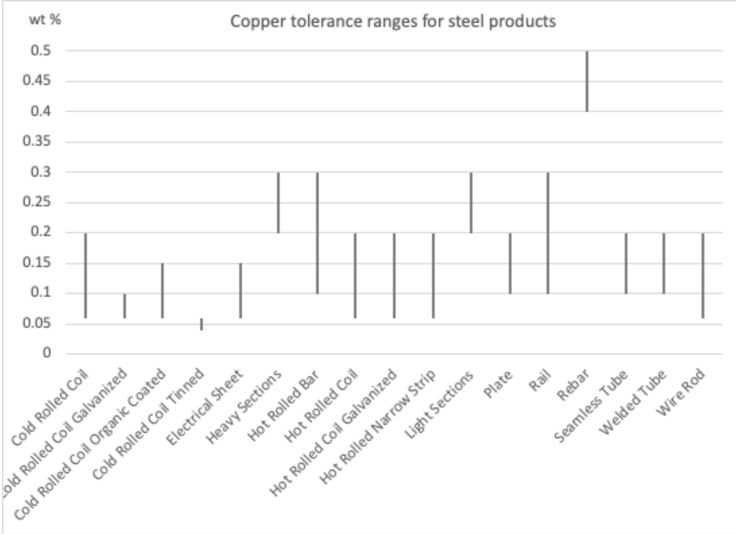

Figure 8. Copper tolerance ranges by steel product (based on Daehn et al. 2017)

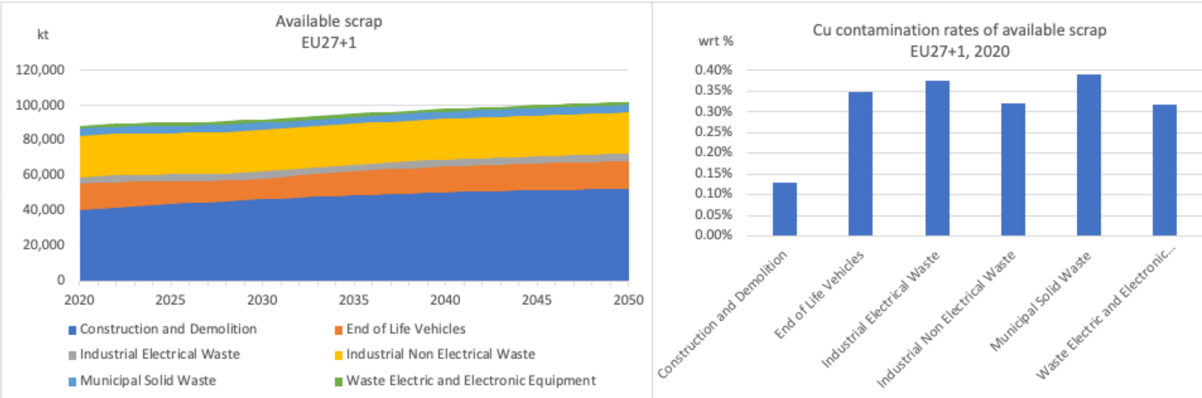

Figure 9. Baseline scrap generation scenario in EU MFA (left) and copper contamination rates of scrap (right), for the EU27+1

Annex

Table 4. Data sources[6] for the main categories of exogenous parameters not derived from other MIC3 modules (the list is non-exhaustive and can change with future model developments)

Sub-module	Parameter	Source
Steel	Lifetimes	Müller et al., 2011
Steel	Production	CAEF, 2008–2019; Eurofer, 2009–2020
Steel	Waste management	World Steel Association, 2010; Daehn et al., 2016; Rostek et al., 2022
Plastics	Lifetimes	Lindner et al., 2019; Material Economics, 2022; Prakash et al., 2016
Plastics	Production	Plastics Europe, 2006-2021
Plastics	Waste management	OECD, 2022, 2023; Plastics Europe, 2022; Klotz et al., 2022, 2023
Cement	Lifetimes	Rostek et al., 2022
Cement	Production	Odyssee-Mure, 2025
Cement	Process characteristics	Alliance for Low-Carbon Cement & Concrete, 2023; Rostek et al., 2022; Shanks et al., 2019
Cement	End use matrix	Cembureau, 2020, 2022, 2023, 2024; VDZ, 2020

[6] Note that the cited data in most cases was not used "as is" but modified.

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