TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

Date: 25/06/2025

D4.5 – Global material flow and trade pilot module

WP4 – Developing satellite modules

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Grant Agreement Number	101137606	**Acronym**	TRANSIENCE
Full Title	TRANSItioning towards an Efficient, carbon-Neutral Circular European industry		
Topic	HORIZON-CL4-2023-TWIN-TRANSITION-01-36		
Funding scheme	HORIZON EUROPE, RIA – Research and Innovation Action		
Start Date	January 2024	**Duration**	48 Months
Project URL	https://www.transience.eu/		
EU Project Advisor	Fatima GONZALEZ GOMEZ		
Project Coordinator	Institute of Communication and Computer Systems (ICCS)		
Deliverable	D4.5 – Global material flow and trade pilot module		
Work Package	WP4 – Developing satellite modules		
Date of Delivery	**Contractual** 30/06/2025	**Actual**	25/06/2025
Nature	Report	**Dissemination Level**	Public
Lead Beneficiary	Potsdam Institute for Climate Impact Research (PIK)		
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Keywords	Satellite module, material flow analysis, model development, model improvement, open source, steel, plastics, cement, global material flows		

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

The open-source repositories created for this deliverable are used within the framework of the Model for European Industry Circularity and Climate Change Mitigation (MIC3) and beyond. The developed material flow analysis (MFA) library (named flodym) is actively promoted as a tool in the industrial ecology community, and already used for the EU MFA in D4.3. The developed global material flow model (named REMIND-MFA) is going to be a satellite module in the MIC3 framework, but also used as a stand-alone tool and coupled to the REMIND integrated assessment model (IAM). Since REMIND is intensively used by a large group of researchers and very well known in its field, this will provide the MFA additional visibility. Other modelling teams and stakeholders will be encouraged to use the model for their own analysis. It will thus inform decision-makers on diverse pathways toward a material-efficient, circular, climate-neutral, sustainable basic material industry.

3. Short summary of results (<250 words)

The REMIND-MFA module is a global MFA model. It will be integrated in the MIC3 framework, informing trade across EU borders and putting MIC3 results into a global context.

REMIND-MFA includes top-down models for the basic materials steel, plastics, and cement, covering 12 world regions (with an optional refinement to 21 regions) through the year 2100. It dynamically projects material demand using gross domestic product (GDP) per capita, and incorporates price-sensitive trade dynamics with a discrete-choice model. The *flodym* software library underpins REMIND-MFA, offering advanced data handling and visualisation capabilities, and improving performance over existing MFA libraries.

Example results include global material flow projections, region-specific production and consumption trends, and a Sankey diagram illustrating plastics flows in 2050. REMIND-MFA delivers scenario modelling for global decarbonisation and circularity, providing vital inputs for the EU MFA. The module's open-source, flexible design ensures accessibility and adaptability. The code structure is the same as in the EU MFA, which eases future linking of both modules.

Future development will enhance input data quality, refine price-sensitive trade modelling, and integrate sector-specific demand models for construction and vehicles. Data sharing via IAMC formats will further expand collaborative research. The model will also be fully documented as part of Task 7.2, in Phase 2 of the TRANSIENCE project.

Ultimately, REMIND-MFA will support Europe's transition to a sustainable, circular, climate-neutral economy by linking regional transitions to global material dynamics.

4. Evidence of accomplishment

- Open-source repositories of
    - the global REMIND-MFA: https://github.com/pik-piam/remind-mfa
    - the MFA library flodym: https://github.com/pik-piam/flodym
- This report.

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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
TECNALIA – Fundación Tecnalia Research & Innovation	ES
UU – Universiteit Utrecht	NL
WI – Wuppertal Institut für Klima, Umwelt, Energie gGmbH	DE
PSI – Paul Scherrer Institut	CH
UCL – University College London	UK

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Executive Summary

This report introduces the REMIND-MFA module, a global material flow analysis (MFA) model developed within the MIC3 framework. REMIND-MFA focuses on three key materials: steel, plastics, and cement, projecting material flows for 12 world regions to 2100. It uses dynamic stock-driven demand projection to estimate future material demand based on GDP per capita, aligning with historical data trends. The model also integrates trade across the material lifecycle, including raw materials, finished goods, and scrap, and features a novel price-sensitive trade module based on discrete-choice modelling.

REMIND-MFA is built on the newly developed *flodym* software library, which offers flexibility and performance improvements over existing MFA libraries. *flodym* manages complex multi-dimensional arrays for flows and stocks as well as streamlines data processing and visualisation.

As part of the broader MIC3 framework, REMIND-MFA enables scenario modelling for material flows in the context of global decarbonisation and circularity performance, providing essential inputs for the EU MFA module. The model's open-source nature and flexible design make it a promising tool for global circular economy assessments also for external users. Key novel features include its global, top-down scope, the integration of price-sensitive trade dynamics, and capacity for future economic coupling with the REMIND IAM.

Exemplary results showcase global material flows, projecting region-specific production and consumption trends, and illustrating global steel flows in 2050 via a detailed Sankey diagram. These results highlight regional consumption peaks and the critical role of recycling in achieving circular economy goals.

Future work will focus on improving input data quality, expanding price-sensitive trade modelling, integrating bottom-up demand models for sectors like construction and vehicles, and enhancing data sharing via IAMC formats. Ultimately, REMIND-MFA will become a robust, adaptable tool to support Europe's transition to a sustainable, circular, climate-neutral economy while linking local transitions to global material dynamics.

Code metadata

Current code version	v.0.1
Link to code repository	https://github.com/pik-piam/remind-mfa
Legal Code License	Open source license (see repository)
Code versioning system used	Git
Software code language	Python
Particular tools, services, modules used	flodym: https://github.com/pik-piam/flodym madrat: https://github.com/pik-piam/madrat
Compilation requirements, operating environments & dependencies	Tested with Python 3.10 and the modules listed in the pyproject.toml file

Note: In earlier deliverables, the global MFA was also referred to under the name SIMSON. It has now been renamed to its final name REMIND-MFA, which is also used throughout the present report.

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1 Introduction

This document presents the REMIND-MFA module, a global material flow analysis (MFA) model. REMIND-MFA constitutes a satellite module in the integrated modelling framework MIC3 designed to explore decarbonisation pathways and circular economy strategies for the basic material industries. As a global MFA module, its primary purpose is to provide the international context essential for evaluating material production, trade, and demand flows—particularly relevant for materials such as steel and plastics, whose supply chains are heavily globalised and trade-intensive.

Given the highly international nature of the basic material sectors, analysing their transformation cannot be effectively undertaken without a robust global perspective. Within the MIC3 framework, which focuses on European industrial decarbonisation and circularity performance, REMIND-MFA addresses this need by delivering a consistent representation of global material trade flows, including those across EU borders. The model interconnections are shown in Figure 1. The trade flows are delivered especially to the EU MFA module (Task 4.3 of the TRANSIENCE project). It takes inputs from the products and services database (Tasks 4.2). Its material flows within Europe are harmonised with those delivered by the EU MFA module (Task 4.3). This enables MIC3 to anchor its European scenarios within a broader international system, accounting for interregional dynamics and trade-related impacts on competitiveness, imports, and exports.

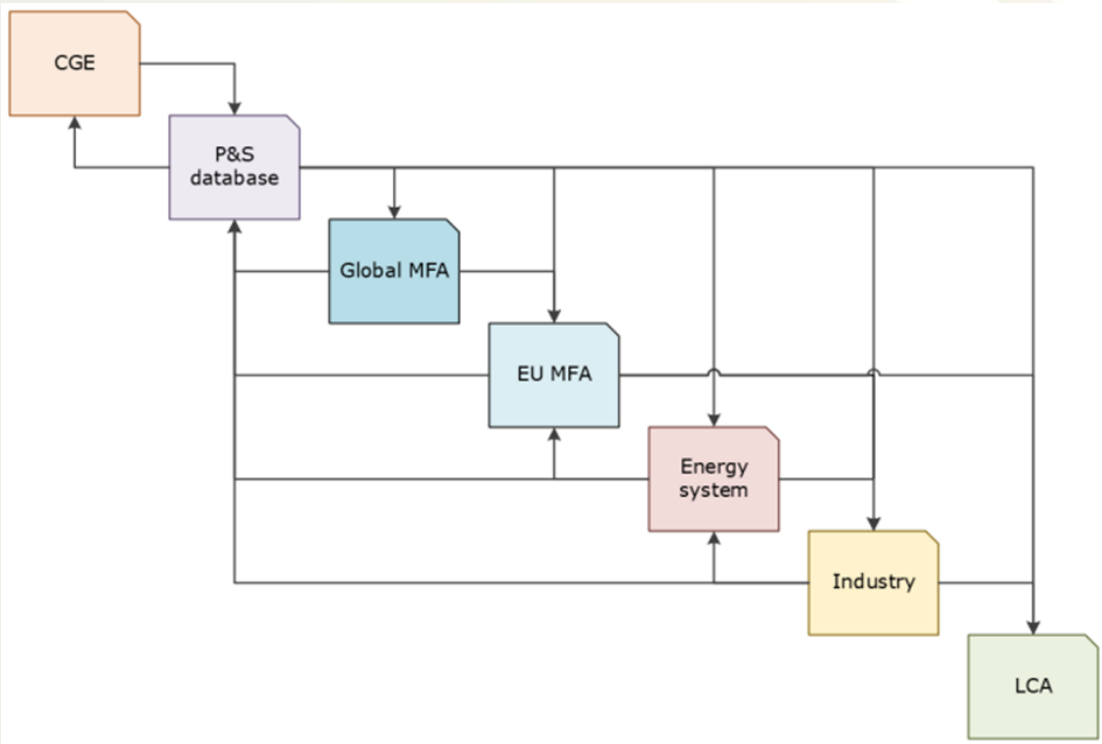

Figure 1. Planned interfaces in the MIC3 baseline workflow from D3.4

While the REMIND IAM, developed and used at PIK, provides advanced global decarbonisation scenarios, it so far lacks detailed material flow representation. REMIND-MFA fills this gap by coupling with REMIND to simulate global material cycles alongside energy system and technological transitions in primary basic material production. Developed from scratch during this project task, REMIND-MFA is equipped to generate scenarios for key global regions, thereby contextualising EU-specific developments within a worldwide framework (later in Task 11.4).

In support of this, the project has also introduced *flodym*, a purpose-built MFA software library designed to ensure flexibility, transparency, and high-quality code for dynamic material flow modelling. Together, REMIND-MFA and *flodym* enable sophisticated analysis of global circular economy potentials and industrial decarbonisation strategies, forming a critical foundation for understanding external impacts and strategic opportunities for the European Union.

2 Module description

This chapter provides an overview of the REMIND-MFA model structure, its core concepts, data inputs and outputs, and code implementation. It lays out the framework and technical details necessary for understanding the model's functioning.

2.1 Concept

This section explains the fundamental principles behind REMIND-MFA, including Dynamic Material Flow Analysis, dynamic stock modelling, material categories covered, stock-driven demand projection, and trade modelling across material life cycles.

2.1.1 Dynamic Material Flow Analysis and Dynamic Stock Modelling

MFA is a systematic approach to quantifying and analysing the flows and stocks of materials within a defined system, such as a city, region, or entire economy. Central to MFA is the concept of social metabolism, which treats societies as metabolic systems that extract materials from the environment, transform them through economic processes, and eventually release wastes and emissions. In MFA, mass balancing ensures that all material inputs, outputs, and accumulations are accounted for according to the conservation of mass principle. These flows and stocks are represented as multi-dimensional arrays, capturing variations across time, region, material type, element, product, and more (Pauliuk et al., 2015).

Dynamic stock modelling is an essential extension of MFA, providing a way to track how materials accumulate in long-lived goods like buildings, infrastructure, and vehicles (Deng et al., 2023). Lifetime models further enrich this picture by quantifying how long materials remain in use before leaving the in-use stock again. They do this via a probability density function of product lifetimes, which determines the share of goods from a certain production year which leave the stock again by a certain time.

2.1.2 Material Modules and Resolution

REMIND-MFA features models for three basic material categories: steel, plastics, and cement. It projects future scenarios of social metabolisms of basic materials in 12 regions covering the whole world (the list of regions is given in Table 1 in the Annex) until the year 2100, in single-year time steps. There is also a model variant, which further refines the two European regions, resulting in a total of 21 world regions.

Figure 2 shows the layouts of the three models including processes and stocks and their linkage through flows. Processes are coloured brown, stocks are grey, and trade is green. The layout is similar across materials, centred around the in-use stock and the material production and fabrication leading up to it. Trade occurs at several steps throughout the life cycle for each material. Recycling flows differ among models. Cement has some unique properties, with limited recycling and negligible product and scrap/waste trade. The flow charts are somewhat simplified. For the full definition of each MFA system including the dimensionality of each stock and flow, refer to the definition files located in the REMIND-MFA GitHub repository under the path remind_mfa/[material]/[material]_definition.py.

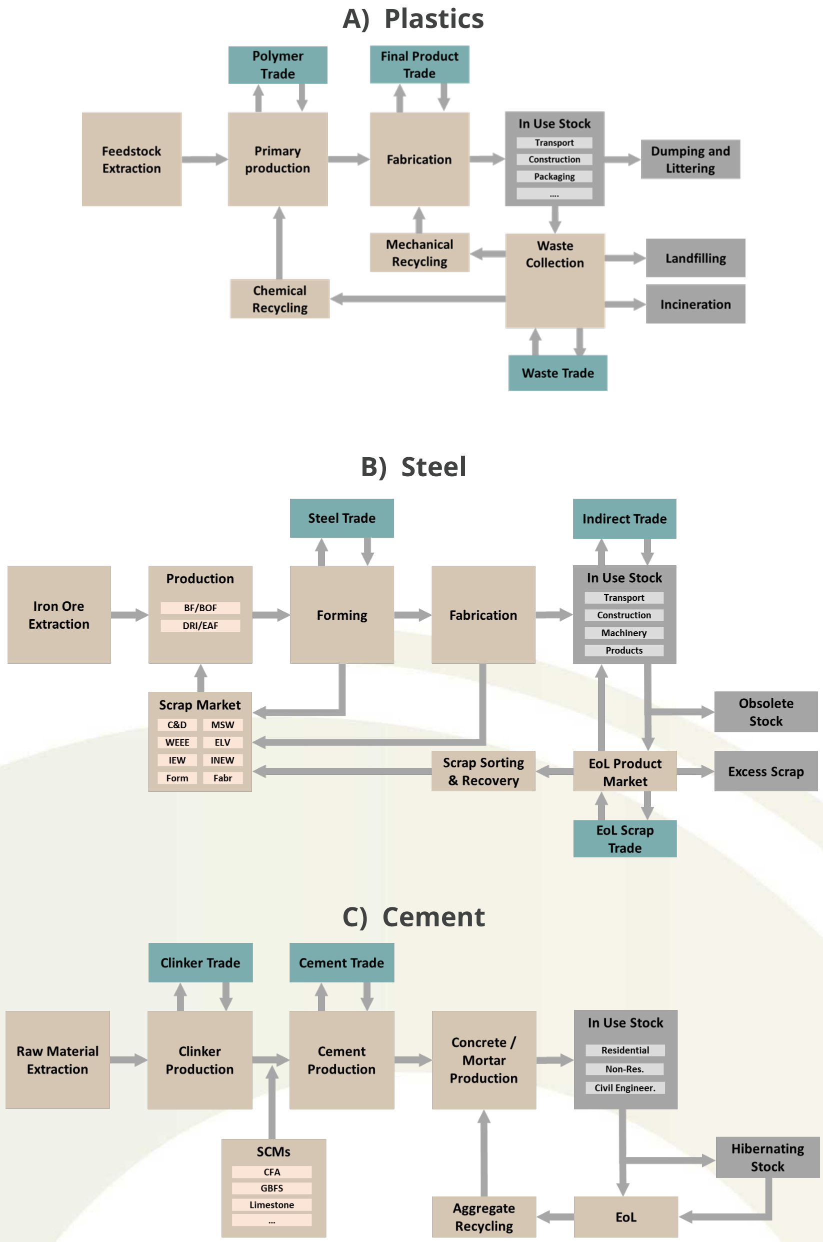

Figure 2. Process and flow layouts for the three materials

2.1.3 Stock-Driven Demand Projection

One key question in prospective material flow analysis is the modelling of future material demand.

Models can be either inflow-driven or stock-driven. In inflow-driven models, demand is modelled first and drives future developments of the in-use stock together with the lifetime model. Stock-driven models, on the other hand, assume that the in-use stock of a material is what provides a service to society, and is therefore the quantity that should be projected as a function of time or GDP, and material demand should be derived from stock change and stock replenishment (Haberl et al., 2017; Lauinger et al., 2021; Pauliuk & Hertwich, 2016).

In REMIND-MFA, we choose such a stock-driven approach, in line with relevant literature in the field (Pauliuk et al., 2013). We use this method to derive a baseline scenario without circular economy (CE) interventions. We assume in-use stock per capita to be a function of GDP per capita (GDPpC). In particular, we assume it to behave like a logit function of the logarithm of GDPpC, which is in line with historic trends. Using historic production data, we calculate historic in-use stock development over GDP. We use these historic stocks to regress the parameters for future stock developments. We do this for separate in-use stocks in different product categories, which then add up to the total in-use stock. For each product category, we regress a common set of parameters for all regions. However, since historic data in single regions deviates from these curves, we apply region-dependent correction terms, which form a smooth transition from historic trends to the common regression[1]. The resulting in-use stock projections for steel are shown in Figure 3. Scenarios with CE interventions are derived from the baseline scenario by adjusting the regress parameters (such as stock saturation levels) or the input parameters (such as lifetimes or recycling rates), or by modifying material demands after regressing them.

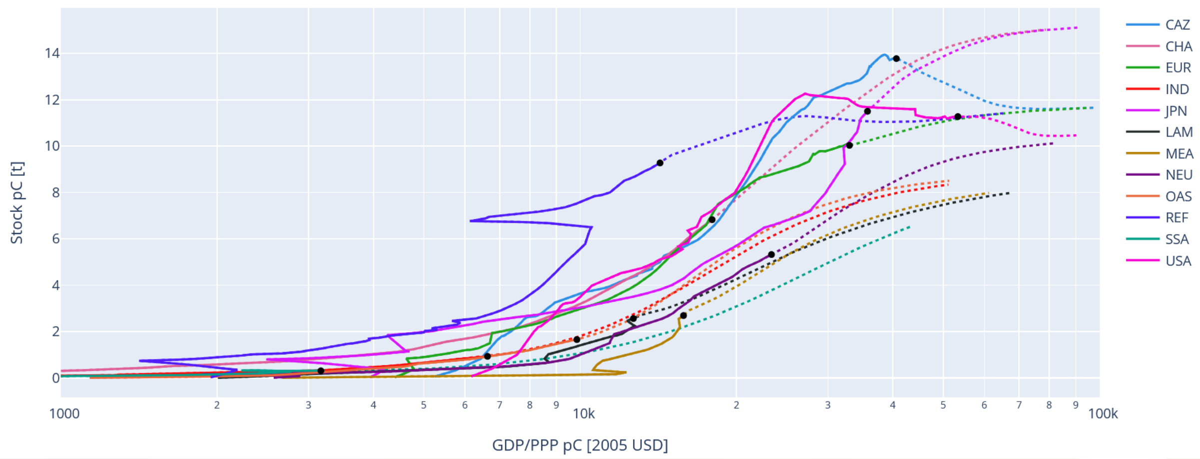

Figure 3. In-use steel stocks per capita; Historic values and projections;
Regions: CAZ: Canada, NZ, Australia, CHA: China, EUR: EU27+1, IND: India, JPN: Japan, LAM: Latin America and the Caribbean, MEA: Middle East, North Africa, Central Asia, NEU: Non-EU27+1 Europe, OAS: Other Asia, REF: Countries from the Reforming Economies of the Former Soviet Union, SSA: Sub-Saharan Africa, USA: USA.

2.1.4 Trade

REMIND-MFA includes trade in different stages across the life cycle (see also Figure 2). Those are raw material trade, trade of materials embedded in goods, and trade of end-of life scrap or waste. Material-specific exceptions apply. Before implementing price-sensitive trade, future trade was modelled as a function of two terms: a fixed fraction of supply or demand of the material at the specific stage (e.g., scrap exports as a fraction of scrap supply), and the absolute trade volumes in

[1] Specifically, we compute the difference both in absolute value and in first derivative of the function, multiply it with a Gaussian blending function, which fades it out over a given time span, and add this difference to the regression. This lets the curve start at historic values and, as the correction terms fade out, blend into the regression towards then end of the century.

the last historic year. In particular, the square root of the product of both was applied. Imports and exports where then scaled in a second step, such that global imports and exports are equal, i.e., that international trade markets clear. Trade is modelled as a pool trade here, i.e., the trade flows of each region have no shares of trade partners defined.

Apart from this, an early version of a price-sensitive trade module was implemented. This model is based on a logit discrete-choice model, with the choices of imports from different regions, or domestic production. The model reacts to temporally changing supply curves (i.e., price structures) in different regions by adjusting trade shares, but it never fully chooses only one option, which corresponds to patterns seen in practice due to heterogeneity of the traded products. Cost penalties for trade are implemented and calibrated to historic data. The implemented cost curves are so far synthetic but will in the future be provided by REMIND IAM. This price-sensitive trade model was tested for raw steel trade. Exemplary results are shown in Section 4.

2.1.5 Circular Economy Measures and Scenarios

The current pilot module represents mostly a "baseline" scenario with no policy interventions. CE interventions are partly implemented as examples (see, e.g., Section 4.2). A comprehensive and systematic framework of policy interventions with a potential grouping into scenario narratives is planned, but not yet ready. It will be implemented in the near future (see also Section 3.2). The model already features a framework for configuration and parametrisation (see also Section 2.3.1), such that the implementational groundwork for this step is already laid.

2.2 Data (inputs and outputs)

This section details the types and formats of input data used by the model, the data processing methods, and the model outputs generated, with emphasis on consistency and integration with other modules.

2.2.1 Inputs

Tables 2-4 in the Annex list the currently used input data sets. Examples include historic production volumes, collection rates, loss rates, or population and GDP projections.

Input data is read in from csv files in pure data frame long format, i.e., one value per row, with one value column and one additional index column per dimension.

However, *flodym* can also handle data read-in from excel files (it is not used in REMIND-MFA due to the improved version control in csv files) and data in wide data frame format, such as with one value column per year. This is already very close to the IAMC format (https://nomenclature-iamc.readthedocs.io) that will used for data sharing in the TRANSIENCE project. In fact, the development of an IAMC format data reader and writer is already in progress in *flodym* and will allow for easy data sharing between EU MFA and global MFA, as well as other satellite modules.

Input data is originally stored in its unedited, raw form. It is then processed with R scripts building on the *madrat* package (Dietrich et al., 2023), which brings them into the form that is used by the MFA. This includes, for example, combining different data sources into one set, filling regional gaps, interpolating in time if necessary, and formatting. *madrat* is a package for transparent and reproducible input data processing developed by PIK (https://github.com/pik-piam/madrat). It takes the regional resolution as an input parameter, such that different resolutions and scopes can be used in the future.

With respect to input data from other MIC3 modules as part of the satellite module coupling and integration, the global REMIND-MFA module has a somewhat special role. Since all the data used in the global model have to be available globally, taking data inputs from other MIC3 modules is not straightforward, if there is no data of this kind for other world regions. This is especially important since the trade flows computed as part of the model rely on a fair comparison between world regions, undistorted by data discrepancies across regions.

So, while some datasets will be used directly (such as GDP trajectories from the macroeconomic module, raw material production curves from EU MFA, or material intensities from the products and services database), the module will rely on harmonisation rather than coupling for most parts. This means that the data of the REMIND-MFA will be adjusted across all world regions to minimise the difference to other MIC3 module results, while ensuring consistency between all world regions.

2.2.2 Outputs

All flows and stocks of all models (See Figure 2) can be written to csv and xlsx files, in the same formats as described for data input in Section 2.2.1. As mentioned earlier, writing data in IAMC format is under development as a functionality.

Some of the output data is visualised in Section 4 as exemplary results.

An important output are trade flows in and out of the EU region of the model, which will be used as input data in the EU MFA as part of the MIC3 integration. This will include raw material, final good, and scrap trade for all materials. Individual material-specific adaptations apply—e.g., final goods for cement are buildings and infrastructure, which are not traded, and neither is end-of-life cement, due to its low value and high transport cost.

2.3 Code and Implementation

This section describes the software tools and libraries powering REMIND-MFA, notably the organisation of the REMIND-MFA source code, as well as the *flodym* library.

2.3.1 REMIND-MFA code structure

The basic structure of the source code is as follows:

- There is one folder for common routines and one folder per material model (plastics, steel, cement)
- For each material, responsibilities are divided to separate files as follows:
    - Definitions of the dimensionalities of flows, stocks, and parameters, as well as the connections of flows and processes.
    - Computing routines for the future MFA system
    - If needed, a similar such file for the historical system

  - Model management: Initialisation of the MFA systems, calls to their compute routines, and to visualisation and export routines
  - Visualisation routines

Besides the source code, the repository contains another folder for configuration files in YAML format, where users can adjust the settings for each run (such as which plots to create, or choosing between different modelling parameters).

This code structure was also adopted by the EU MFA module in MIC3, enabling close integration of both models.

2.3.2 The *flodym* library

The most-used library for dynamic material flow analysis to this date is ODYM (Pauliuk & Heeren, 2020). In the course of this project, a first draft version of REMIND-MFA was implemented in ODYM. However, this version was discarded. Instead, it was decided to perform a re-implementation, to enable the resulting MFA code to be simple and flexible for subsequent changes and extensions. The most important novelties of *flodym* are:

- A FlodymArray object which manages the multi-dimensional operations of one or several arrays such as flows, stocks, parameters, or trades, based on the dimensions given at initialisations. This allows to change the number or order of dimensions, and the number and order of items in each dimension, with minimal changes to the code.
- Integrating the data structures for handling a material stock based on a lifetime model with those of the whole MFA system (they were two separate entities in ODYM), and making them work on multi-dimensional arrays instead of just scalars. This has benefits for code simplicity and performance.
- A simplified, more flexible, and much more performant data read-in
- Visualisation and export routines (all the result figures in this report are created with *flodym* visualisation routines).
- An extended functionality with respect to dynamic stock models and lifetime models
- Extensive documentation under https://flodym.readthedocs.io/

EU MFA in D4.3 now also builds on *flodym*, which paves the way to a close code integration of both MFA models.

3 Novelty and next steps

Chapter 3 highlights the unique aspects of REMIND-MFA compared to existing models and outlines planned improvements and expansions to enhance its accuracy, usability, and integration capabilities in future development.

3.1 Novelty

REMIND-MFA as well as *flodym* were written form scratch in the course of TRANSIENCE Task 4.5 leading up to this deliverable, such that the whole model is new.

To our knowledge, no other top-down MFA with our regional, temporal, and material scope exists. There are some bottom-up models for certain product categories (Pauliuk et al., 2021; Zhong et al., 2021). These models are, however, not exhaustive in terms of use sectors, such that overall material demands cannot be derived from them. What is more, they have different regional and temporal scopes from REMIND-MFA. The MISO2 model (Wiedenhofer et al., 2024) is a top-down model with global scope and all major basic materials, but only runs up to 2015 and does not include projections into the future.

So, in being a global, open-source, top-down, prospective MFA for all three most important basic materials already makes this model unique. However, there are also some features that set it apart from existing models:

- The model will incorporate an economic module, using price-dependent parameters. This will be especially important when soft linking the model to REMIND. This inclusion of price sensitivities is so far rarely found in MFA models. It is still in early development stage.
- The inclusion of a price-sensitive trade model in MFAs is also new. This part is already functional, though at an early stage.
- Through the use of *madrat* and *flodym*, the regional and temporal scope and resolution can be varied. This makes the model attractive to be used by other groups, who can adapt it to their needs.

Altogether, these unique features and adaptable components make REMIND-MFA a promising foundation for advancing material flow analyses on a global scale.

3.2 Next Steps

We plan on continuously improving the model quality and expanding its functionality. In particular, this includes:

- Refining the used input data, replacing global values with region-specific values where they are available
- Adding bottom-up demand projections for selected use sectors, such as buildings and vehicles, and having them replace top-down demand projections for these sectors.
- Expanding and improving the price-sensitive trade model
- Adding price-sensitive parameters aside from trade, and embedding them in an integrated

economic module

- Adding IAMC format reading and writing
- Coupling and harmonising with the EU MFA and other MIC3 satellite modules
- Implementing a systematic and comprehensive framework of circular economy interventions and grouping them into scenario narratives
- Fully documenting the model and its input data

These steps will help ensure that REMIND-MFA becomes an even more robust and versatile tool for understanding material flows in the future and is able to serve as an integral part of the MIC3 framework.

4 Exemplary Results

This section showcases some exemplary results generated by the REMIND-MFA model to demonstrate its capabilities. These results highlight different aspects of the model and its potential applications. A range of potential results is chosen across material models, but similar results can also be produced for the respective other materials.

4.1 Steel Consumption Projections

Steel consumption in a business as usual (BAU) scenario is shown in Figure 4. The 12 regions of REMIND-MFA are shown separately. For region definitions, refer to Table 1 in the Annex. The historical scope extends from 1900 to 2100, to show both historical developments and future projections.

REMIND-MFA derives steel consumption directly from the in-use stock regression and then calculates production from this, taking into consideration trade in both raw material and finished goods, as well as applying fabrication losses. The future development of trade is highly uncertain. In addition to raw material production, steel consumption can therefore be interesting to look at, as the projections of this quantity do not include the trade uncertainties in a model driven by in-use stocks.

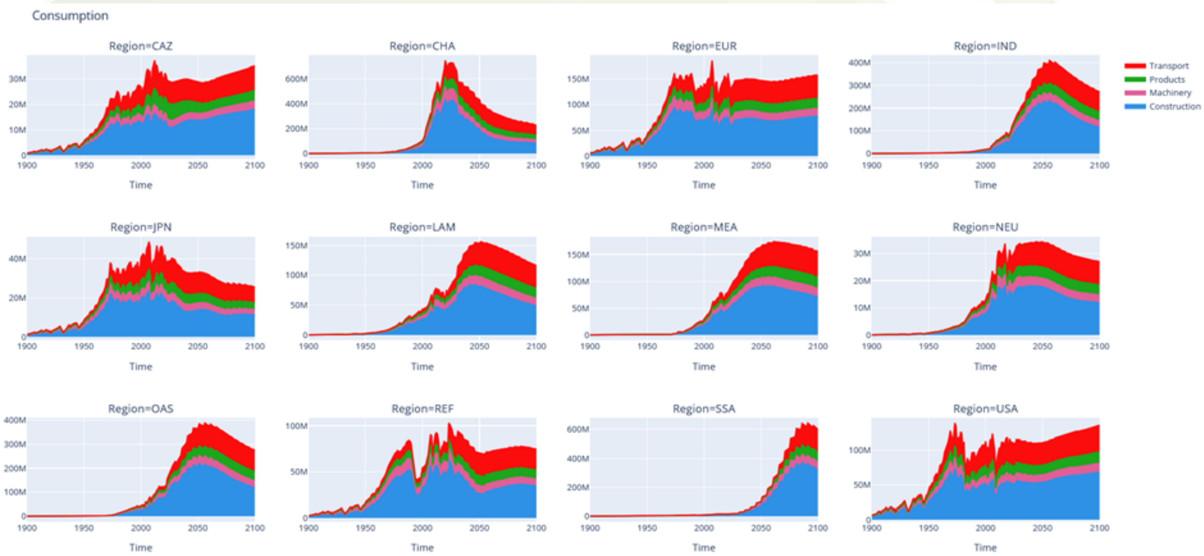

Figure 4. Steel consumption by product category; Historic values and projections;
Regions: CAZ: Canada, NZ, Australia, CHA: China, EUR: EU 28, IND: India, JPN: Japan, LAM: Latin America and the Caribbean, MEA: Middle East, North Africa, Central Asia, NEU: Non-EU27+1 Europe, OAS: Other Asia, REF: Countries from the Reforming Economies of the Former Soviet Union, SSA: Sub-Saharan Africa, USA: USA.

The data shows stagnating or slightly declining consumption in the developed economies in the EU, USA, Japan and Oceania. It shows a decrease in China, which is currently experiencing overcapacities and is expecting declining consumption. Consumption is rising in developing economies, and is projected here to reach a peak around the middle of the century for India, other Asia, Middle East/Northern Africa, and Latin America. In sub-Saharan Africa, the peak is reached towards the end of the century.

4.2 Cement Production and Process Emissions

Exemplary cement MFA results are shown in Figure 5 for three selected regions (China, India, and the USA) under different global concrete stock convergence scenarios. A conservative baseline scenario assumes saturation slightly above current EU levels. A low-demand scenario reflects higher material efficiency through lower saturation. For emissions, we add a low-demand CE scenario with a linear global reduction in clinker ratios to 60%. Since clinker is the most emission-intensive component of cement, reducing its share will reduce emissions.

After peaking in 2020, Chinese production declines by the end of the century. Fluctuations continue due to infrastructure renewal. Indian production grows more than two-fold by 2070; the low-demand scenario reduces this peak by 20%. The US production increases slightly by 2050, driven by stock growth. Emissions (Figure 3 (b)) mirror demand. In the low-demand CE case, US emissions drop significantly in the second half of the century due to historically high clinker ratios. In contrast, China's already low clinker ratios leave little room for further cuts, and emissions remain unchanged between low-demand and low-demand CE scenarios.

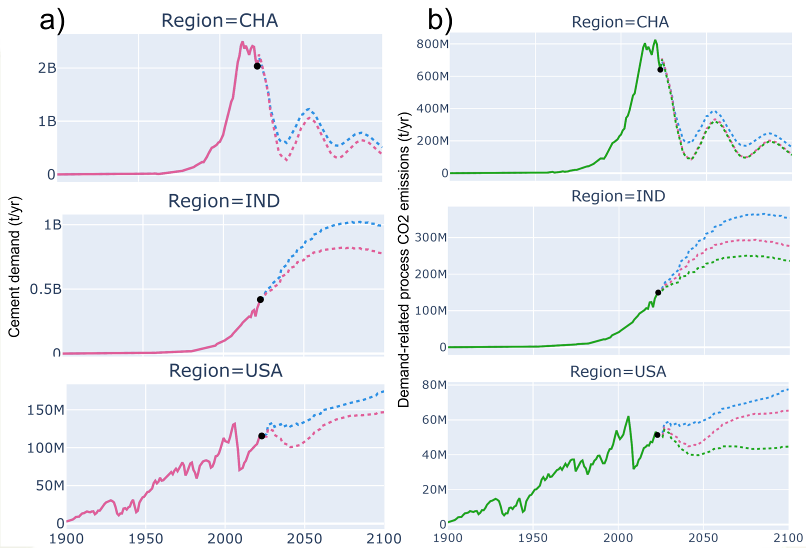

Figure 5. Historic (solid line) and projected (dotted) cement production (a) and process emissions (b) in selected regions. Top: China, centre: India, bottom: USA. Baseline scenario in blue, low-demand scenario in magenta and low-demand in green.

4.3 Global Plastics Carbon Flows in 2050

The Sankey diagram in Figure 6 illustrates the global flows of plastics carbon in 2050 in a moderate circular economy scenario across different phases of the product life cycle: production, processing, use, recycling, and waste treatment. The material metabolism starts with different production routes, from fossil oil or based on different carbon cycles. From there, plastic carbon moves through various stages, including fabrication and eventual use in different sectors. At the end of their life, a fraction of the plastics contained in products enters one of the recycling loops, contributing to new plastics production (mechanical or chemical recycling, or a carbon cycle

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through incineration, atmospheric carbon and subsequent biogenic production). But a significant share enters waste treatment instead (landfilling or incineration) or is mismanaged and released into the environment. Trade is not shown here, as it is a global balance, where imports and exports cancel out.

The diagram highlights the different circularity options for the "recycle" strategy alone and its importance for both decarbonisation and reducing environmental impacts of plastic waste, thereby hinting to synergies and other interactions between circularity performance and decarbonisation. The diagram will be helpful in delivering a visual representation of the effect of circular economy measures.

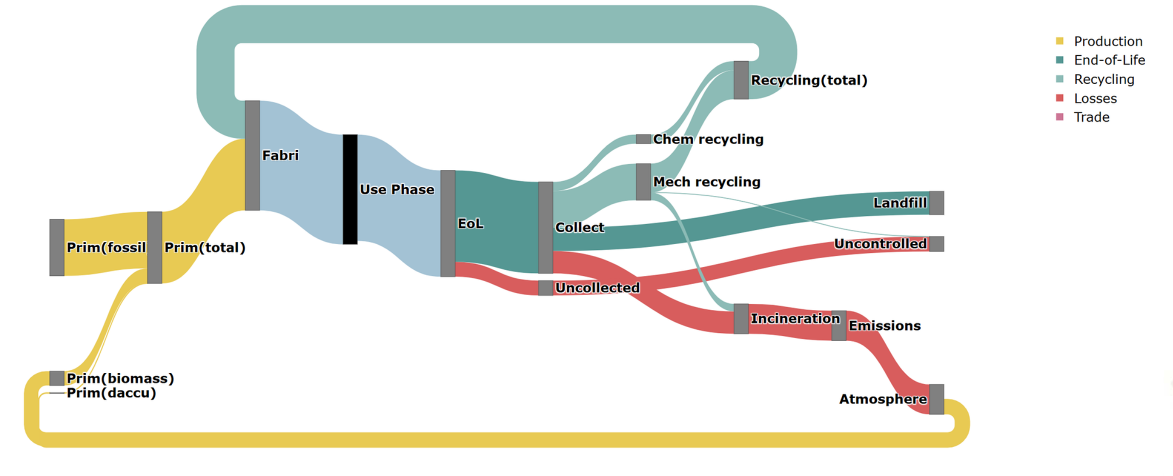

Figure 6. Global plastics carbon flows in 2050

4.4 Steel Trade

Figure 7 demonstrates the response of the price-sensitive trade model to price changes in two scenarios: high European production cost (Scenario A) and low European production cost (Scenario B). It presents the trade flows of steel for the EU (EUR) and China (CHA) as a key trading partner, with solid lines representing imports and dashed lines representing exports. The time axis again spans from 1900 to 2100.

The scenarios and figure are intended as a demonstrator of the trade model mechanics. In Scenario A, with high production costs in Europe, imports in Europe steadily increase while exports decrease, as Europe relies more on imported steel as domestic production becomes costlier. In contrast, China's exports rise significantly after 2020, with a notable decline in imports.

In Scenario B, with lower European production costs, Europe's imports remain relatively flat or decrease over time, while exports rise, indicating improved competitiveness of European steel on the global market. In this scenario, China's exports are still significant but show a less dramatic increase compared to Scenario A, while imports remain low.

The imports and exports are gained from an aggregation of country-specific trade data, which however does not differentiate trade flows by trade partner. For multi-country regions such as the

EU, the aggregation therefore also counts intra-region, inter-country trade (such as between two EU countries) towards imports and exports. This can be remedied in the future by either incorporating bilateral trade data, or only considering net trade, where intra-region trade cancels in the balance.

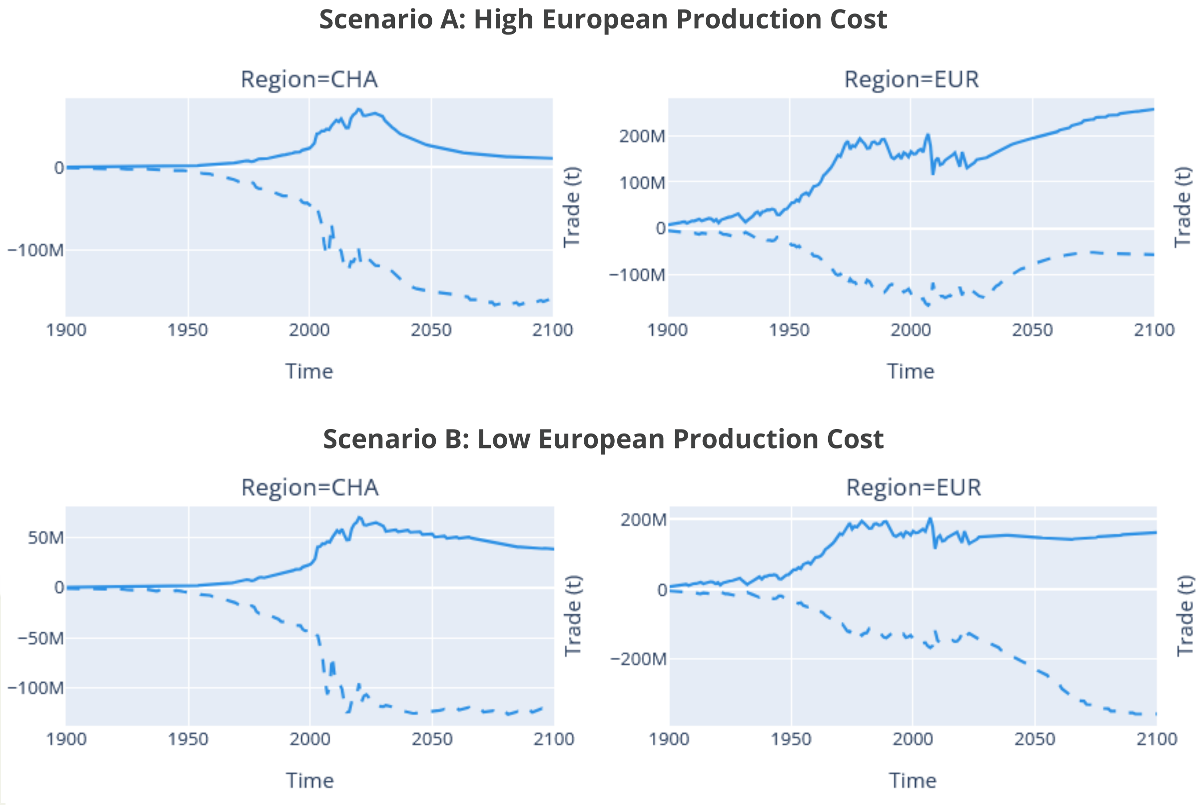

Figure 7. Trade model demonstration for Regions China (CHA) and EU27+1 (EUR); Imports are solid, exports are dashed; Reaction of trade flows to price changes in two scenarios. Results are only meant for model demonstration

ANNEX

Region definitions

Table 1. Regional definitions of REMIND-MFA

Code	Name	Full list of countries
CAZ	Canada, NZ, Australia	Canada, Australia, New Zealand, Heard & McDonald Islands, St. Pierre & Miquelon
CHA	China	China, Hong Kong, Macau, Taiwan
EUR	EU 27+1	Austria, Belgium, Bulgaria, Cyprus, Czechia, Germany, Denmark, Spain, Estonia, Finland, France, Faroe Islands, United Kingdom, Gibraltar, Greece, Greenland, Hungary, Isle of Man, Ireland, Italy, Jersey, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Sweden
IND	India	India
JPN	Japan	Japan
LAM	Latin America and the Caribbean	Aruba, Anguilla, Argentina, Antigua & Barbuda, Bahamas, Belize, Bermuda, Bolivia, Brazil, Barbados, Chile, Colombia, Costa Rica, Cuba, Cayman Islands, Dominica, Dominican Republic, Ecuador, Falkland Islands, Guadeloupe, Grenada, Guatemala, French Guiana, Guyana, Honduras, Haiti, Jamaica, St. Kitts & Nevis, St. Lucia, Mexico, Montserrat, Martinique, Nicaragua, Panama, Peru, Paraguay, El Salvador, Suriname, Turks & Caicos Islands, Trinidad & Tobago, Uruguay, St. Vincent & Grenadines, Venezuela, British Virgin Islands, U.S. Virgin Islands, Puerto Rico, U.S. Virgin Islands
MEA	Middle East, North Africa, Central Asia	United Arab Emirates, Bahrain, Algeria, Egypt, Western Sahara, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Palestinian Territories, Qatar, Saudi Arabia, Sudan, Syria, Tunisia, Yemen
NEU	Non-EU27+1 Europe	Albania, Andorra, Bosnia & Herzegovina, Switzerland, Guernsey, Croatia, Iceland, Liechtenstein, Monaco, North Macedonia, Montenegro, Norway, Nauru, Svalbard & Jan Mayen, San Marino, St. Pierre & Miquelon, Serbia, Turkey, Vatican City
OAS	Other Asia	Afghanistan, American Samoa, Bangladesh, Brunei, Bhutan, Cocos (Keeling) Islands, Cook Islands, Christmas Island, Fiji, Micronesia (Federated States of), Guam, Indonesia, Cambodia, Kiribati, South Korea, Laos, Sri Lanka, Maldives, Marshall Islands, Myanmar (Burma), Mongolia, Northern Mariana Islands, Malaysia, New Caledonia, Norfolk Island, Niue, Nepal, Pakistan, Pitcairn Islands, Philippines, Palau, Papua New Guinea, North Korea, French Polynesia, Singapore, Solomon Islands, Thailand, Tokelau, Timor-Leste, Tonga, Tuvalu, Vietnam, Vanuatu, Wallis & Futuna, Samoa
REF	Countries from the Reforming Economies of the Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
SSA	Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo-Brazzaville, Congo-Kinshasa, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Réunion, Rwanda, São Tomé & Príncipe, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Tanzania, Togo, Uganda, Zambia, Zimbabwe
USA	USA	United States of America

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Input Data Sets

A) Plastics

Table 2. Input data sets for the plastics MFA

Dataset Name	Description
collection_rate	Fraction of plastic waste that is collected from total generated waste.
mechanical_recycling_rate	Fraction of collected plastic waste that is mechanically recycled.
chemical_recycling_rate	Fraction of collected plastic waste that is chemically recycled.
solvent_recycling_rate	Fraction of collected plastic waste that is solvent-based recycled.
incineration_rate	Fraction of collected plastic waste that is incinerated for energy recovery.
landfill_rate	Fraction of collected plastic waste that is disposed of in landfills.
wasteimport_rate	Rate of plastic waste imported from other regions or countries.
wasteexport_rate	Rate of plastic waste exported to other regions or countries.
bio_production_rate	Fraction of plastic production sourced from bio-based materials.
daccu_production_rate	Fraction of plastic production using direct air capture and carbon utilization (DACCU).
mechanical_recycling_yield	Yield of usable recycled plastic from mechanical recycling processes.
reclmech_loss_ uncontrolled_rate	Loss rate of plastic materials during mechanical recycling processes due to uncontrolled factors.
material_shares_in_goods	Fraction of different plastics (materials) used in various goods.
emission_capture_rate	Fraction of emissions captured from plastic production or disposal processes.
carbon_content_materials	Carbon content in various plastic materials (e.g., PET, HDPE).
wasteimporttotal	Total amount of plastic waste imported to a region or country.
finalimporttotal	Total amount of final plastic products imported to a region or country.
production	Production volume of various plastic goods or materials.
lifetime_mean	Average lifetime of plastic goods before becoming waste.
lifetime_std	Standard deviation of the lifetime of plastic goods.
population	Population of regions, used to project future plastic demand.
gdppc	Gross Domestic Product per capita, used to project future plastic demand.
mechanical_recycling_rate	Mechanical recycling rate by time and material type.

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B) Steel

Table 3. Input data sets for the steel MFA

Dataset Name	Description
forming_yield	Yield in forming processes.
fabrication_yield	Yield during fabrication, varies by good type.
recovery_rate	EOL Material recovery rate by good type.
external_copper_rate	External copper usage rate by good type.
cu_tolerances	Copper content tolerances for different intermediate types.
good_to_intermediate_distribution	Distribution from final goods to intermediates by good and intermediate type.
production	Total production by historical period and region.
production_by_intermediate	Production split by intermediate type, historical period, and region.
intermediate_imports	Imports of intermediate goods by period, region, and intermediate type.
intermediate_exports	Exports of intermediate goods by period, region, and intermediate type.
indirect_imports	Indirect imports (via trade) by period, region, and good type.
indirect_exports	Indirect exports (via trade) by period, region, and good type.
scrap_imports	Imports of scrap materials by period and region.
scrap_exports	Exports of scrap materials by period and region.
population	Population data by time and region.
gdppc	GDP per capita by time and region.
lifetime_mean	Mean lifetime of goods in stock by region and good type.
lifetime_std	Standard deviation of lifetime for goods in stock by region and good type.
sector_split_low	Sectoral split for low economic growth scenarios by good type.
sector_split_medium	Sectoral split for medium economic growth scenarios by good type.
sector_split_high	Sectoral split for high economic growth scenarios by good type.
secsplit_gdppc_low	Sectoral split for low GDP per capita scenarios (no additional dimensions).
secsplit_gdppc_high	Sectoral split for high GDP per capita scenarios (no additional dimensions).
scrap_consumption	Scrap consumption by period and region.
max_scrap_share_base_model	Maximum scrap share in the base model.
scrap_in_bof_rate	Scrap usage rate in Basic Oxygen Furnace (BOF) process.
forming_losses	Losses during forming.
fabrication_losses	Losses during fabrication.
production_yield	Overall production yield.
saturation_level_factor	Factor for saturation level by region.
stock_growth_speed_factor	Factor for the speed of stock growth by region.

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C) Cement

Table 4. Input data sets for the cement MFA

Dataset Name	Description
cement_production	Cement production by historical period and region.
clinker_ratio	Ratio of clinker in cement production.
cement_ratio	Ratio of cement in concrete.
use_split	Split of cement use by sector.
use_lifetime_mean	Mean lifetime of cement in use by sector.
use_lifetime_std	Standard deviation of lifetime for cement in use by sector.
population	Population by time and region.
gdppc	GDP per capita by time and region.

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