TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

Date: 18/12/2025

MS13 – Opening the beta-version modules

WP7 – Operationalisation of the open modular framework

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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 report will be primarily used by the funding agency and the TRANSIENCE consortium to understand current progress on model development within the project. The report can also be used by modellers and scientists beyond the project as it provides an overview of all modelling resources that have been developed to date.

3. Short summary of results (<250 words)

This milestone report (MS13) marks the opening of beta versions of the TRANSIENCE modules, which will form the MIC3 open-source modelling framework for assessing industrial circularity, decarbonisation, and sustainability in Europe. The report provides links to updated code repositories and online documentation for all modules, ensuring transparency and usability. Apart from the and the P&S Database that is also part of the MIC3 ecosystem, seven core modules—EU-MFA and REMIND-MFA, FORECAST-Sites and ITOM, LCA-TRANSIENCE, OPEN-GEM, and OPEN-PROM—have been enhanced since their initial release in mid-2025. Key improvements include the integration of top-down and bottom-up approaches, advanced functionalities such as carbon capture options, scenario variation, harmonisation across modules, and improved data quality. Online documentation has been expanded for all modules to support external uptake. The report also outlines progress toward integration into MIC3, including a linking methodology, harmonised assumptions, and prioritised data exchange. By opening beta versions and establishing robust documentation and integration strategies, TRANSIENCE lays the foundation for a comprehensive modelling ecosystem that supports Europe's transition to a circular, climate-neutral, and sustainable industrial future.

4. Evidence of accomplishment

This report, as well as the beta versions and online documentation of all modules on GitHub and Read the Docs:

Name	Link to codebase	Link to documentation
EU-MFA	https://github.com/wupperinst/transience-eu-mfa/	https://transience-eu-mfa.readthedocs.io/en/latest/
FORECAST-Sites	https://github.com/fraunhofer-isi/forecast-sites	On the same link as the codebase
ITOM	https://github.com/wupperinst/itom	https://itom.readthedocs.io/en/latest/
LCA-TRANSIENCE	https://github.com/tomterlouw/lca_transience	On the same link as the codebase
OPEN-GEM	https://github.com/e3modelling/OPEN-GEM	https://e3modelling.github.io/OPEN-GEM/ and on the same link as the codebase.
OPEN-PROM	https://github.com/e3modelling/OPEN-PROM	https://e3modelling.github.io/OPEN-PROM/ (including tutorials)
REMIND-MFA	https://github.com/pik-piam/remind-mfa	https://remind-mfa.readthedocs.io/en/latest/

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 milestone report (MS13) provides an update on the beta versions of the TRANSIENCE modelling components, which form the foundation of the open modular framework **MIC3**. The goal of TRANSIENCE is to develop a transparent, interoperable, and fully open-source model ecosystem to assess industrial circularity, decarbonisation, and sustainability in Europe.

Key Highlights include:

- **Module Development:** Seven core modules—EU-MFA and REMIND-MFA, FORECAST-Sites and ITOM, LCA-TRANSIENCE, OPEN-GEM, and OPEN-PROM—have been enhanced since their initial release in mid-2025. Updates include:
  - Integration of top-down and bottom-up approaches for material flows.
  - Advanced functionalities such as process chains, carbon capture options, and scenario variation frameworks.
  - Improved data quality, harmonisation across modules, and expanded documentation.
- **Open Documentation:** All modules now feature public GitHub repositories and online documentation to ensure transparency, usability, and uptake by external modelling teams.
- **Progress toward integration into MIC3:** A linking methodology has been established, focusing on:
  - Harmonised assumptions (e.g., energy prices, biomass availability).
  - Prioritised data exchange between modules (material flows, energy demand, CO_2 pricing).
  - Development of workflows for initial integration tests and consistency checks.
- **Case Studies:** Modules are being validated in four industrial clusters (Basque Country, Port of Rotterdam, Rhine-Ruhr, and Silesia) and at the EU level. Insights from these studies will inform the final module versions (to be documented in deliverable D7.4, due in December 2026).

In terms of next steps, we will proceed with full integration of modules into MIC3, the harmonisation of data formats (using the IAMC template), a final refinement of documentation, as well as the incorporation of stakeholder feedback.

By opening beta versions and establishing robust documentation and integration strategies, TRANSIENCE sets the stage for a comprehensive modelling framework that supports Europe's transition to a circular, climate-neutral industrial future.

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1 Introduction

The purpose of this milestone report is to provide an update on the modules developed and enhanced in the context of WP4 (to be integrated in the context of WP7) of the TRANSIENCE project. The first version of the modules was completed around the end of the first reporting period of TRANSIENCE (May-June 2025). These first versions were extensively described in the respective WP4 deliverables, including D4.1 ('Socioeconomic module'), D4.2 ('Service and product database'), D4.3 ('EU material and sectoral flow pilot modules'), D4.4 ('EU industrial pilot modules'), D4.5 ('Global material flow and trade pilot module'), D4.6 ('Energy system pilot module', and D4.7 ('Environmental impact assessment'). All these deliverables are publicly available on the project website[1].

The WP4 deliverables provided details about the conceptual framework of each module and the input and output data that are used. The deliverables also included a comprehensive justification on the novelty of its modules, the next steps in their development and their interlinkage to the MIC3 model, and—for some modules—exemplary results. The modules are currently validated in four case studies that are taking place as part of WP8 in pertinent industrial clusters in Europe (Basque country in Spain, Port of Rotterdam in the Netherlands, Rhine-Ruhr in Germany, and Silesia in Poland) as well as in a fifth study on industrial transformation at the EU level. Based on the progress of the case studies, the modules will be further upgraded to ensure their usefulness and relevance to other applications throughout Europe. The final version of the modules will be described in deliverable D7.4, due in December 2026.

Milestone MS13 acts as an intermediate step between their initial versions on the WP4 deliverables and their final versions in D7.4. This report includes links to the updated code repositories for all TRANSIENCE modules on GitHub as well as links to their online documentation (see Section 2). While some of the modules already had an online documentation page since their first version, this has been now extended to all modules, while previous documentation pages have been further enhanced.

Next, Section 3 of the report provides an overview of all model development that has taken place between the release of WP4 deliverables in Months 17-18 (May-June 2025) and the midterm of the project in Month 24 (i.e., December 2025). For each module, the report provides a list of updates from the initial model version as well as next steps towards the final module version (December 2026) and discusses potential requirements for the case study work in WP8. These updates are provided in a concise way as the exact changes are publicly visible on the GitHub repositories and will be described in detail in Deliverable D7.4.

Finally, Section 4 includes a comprehensive list for each module of all the data inputs that are expected from other modules, in the context of their integration to the MIC3 modelling framework. Along with the updates of the modules, model linking will be an ongoing activity throughout the second phase of the project and will be comprehensively documented in deliverables D7.2 ('Data coordination and API documentation', due in June 2026) and D7.3 ('MIC3 operational version', due in November 2026).

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[1] https://www.transience.eu/publications/deliverables

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2 Online documentation

Table 1 shows links to the public GitHub repositories where each module is provided as open source, along with links to the online documentation page that was created for each module. As shown by the statistics of the GitHub repositories, code updates from the first version of the models in May and June 2025 to the publication of this report in December 2025 occurred in different frequency for each module. For instance, the OPEN-PROM module was frequently updated during the last six months[2], while the LCA module was updated in one go in November 2025[3]. For a summary of the changes for each module see Section 3, while for more details on the exact code that was changed see the GitHub repositories on Table 1. It is noted that some of the modules are using the Product and Services (P&S) database that was developed in the context of WP4 and has its own repository[4] and documentation[5]. While the database has also been enhanced since its original release and may be further enhanced in the future, it is of different nature and is not expected to follow the same update cycles as the one of the modules; therefore, it is not discussed in this report.

Table 1. Links to the codebase and documentation of all TRANSIENCE modules

Name	Link to codebase	Link to documentation
EU-MFA	https://github.com/wupperinst/transience-eu-mfa/	https://transience-eu-mfa.readthedocs.io/en/latest/
FORECAST-Sites	https://github.com/fraunhofer-isi/forecast-sites	On the same link as the codebase
ITOM	https://github.com/wupperinst/itom	https://itom.readthedocs.io/en/latest/
LCA-TRANSIENCE	https://github.com/tomterlouw/lca_transience	On the same link as the codebase
OPEN-GEM	https://github.com/e3modelling/OPEN-GEM	https://e3modelling.github.io/OPEN-GEM/ and on the same link as the codebase.
OPEN-PROM	https://github.com/e3modelling/OPEN-PROM	Documentation: https://e3modelling.github.io/OPEN-PROM/ Tutorials: https://github.com/e3modelling/OPEN-PROM/tree/main/tutorials
REMIND-MFA	https://github.com/pik-piam/remind-mfa	https://remind-mfa.readthedocs.io/en/latest/

The development of online documentation for all modules was also an important change from the first module versions in WP4. Having an online documentation that can easily stay up to date with the updates

[2] https://github.com/e3modelling/OPEN-PROM/graphs/code-frequency
[3] https://github.com/tomterlouw/lca_transience/graphs/code-frequency
[4] https://zenodo.org/records/15517592
[5] https://zenodo.org/records/15517804

of the model code is critical for the uptake of the open-source modules by other modelling teams and for building trust in the modules and, subsequently, their results. Using project deliverables can be a useful first step toward comprehensive documentation, but such reports offer only a static snapshot of a model's functionality and may confuse users. For instance, even when updated reports are published regularly, users may still encounter outdated versions that no longer correspond to the current model.

As shown in **Table 1**, different methods were used to create the online documentation of the TRANSIENCE modules. Some of the models provided documentation directly on the README section of their GitHub repositories or on GitHub Pages[6], while others developed separate pages in the Read the Docs platform[7]. While the documentation pages do not have the same structure for all modules, most of them include information about the installation of a module, its main features, and its input and output data. To ensure comprehensive and consistent documentation across MIC3 modules, a shared online documentation structure will be agreed with all modelling teams as part of the upcoming module updates in 2026. A draft structure is provided below, synthesising elements already documented by some modules.

- Homepage (overview of all other pages)
- First steps
    - Installation
    - Tutorial
- Model overview
    - Context and main features
    - Structure (e.g., submodules)
    - Mathematical foundation
    - Code organisation
- Parameters
    - Data inputs
    - Configuration
    - Constraints
    - Data outputs
- Integration with other models of the MIC3 framework
    - Inputs from other modules
    - Outputs to other modules

[6] https://docs.github.com/en/pages
[7] https://docs.readthedocs.com/platform/stable/tutorial/index.html

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3 Model development: progress and next steps

This section provides an overview of all model updates done in the context of MS13 (i.e., within the last six months), any work pending as part of Task 7.2 towards the final version of the models (Deliverable D7.4), and modelling requirements for addressing the case studies of WP8. As model development is still in progress, planned additions and modifications for each module may change, especially to adapt to the needs of the WP8 case studies. Future updates will be continuously documented in the online documentation page for each module (see Section 2), while Deliverable D7.4 will provide a detailed description of the final module versions in the context of TRANSIENCE.

3.1 EU-MFA

3.1.1 Updates from the initial module version

As described in Deliverable D4.3 (‘*EU material and sectoral flow pilot modules*’), the next steps for the second phase of the project include the 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 REMIND-MFA module), automated visualisations, and complete documentation. Since the release of the first version of the EU-MFA, relevant progress has been made on all these points to date:

- The integration between the top-down and bottom-up approach previously implemented for cement and buildings was comprehensively validated.
- The integration was generalised and mappings for buildings and vehicles to plastic and steel product streams were created. The roll-out to plastics and buildings, plastics and vehicles, steel and buildings as well as steel and vehicles was prepared.
- The harmonisation between the EU-MFA and the REMIND-MFA module was advanced by mapping product categories of trade flows to each other.
- A first version of automated and interactive visualisations was implemented for plastics and steel.
- The documentation was updated to reflect all the above-mentioned changes.

3.1.2 Next steps towards the final module version

Building on the previously mentioned updates to the initial module version, the following steps are planned for the finalisation of the EU-MFA module in the second project phase:

- Roll-out of the integration between the top-down and bottom-up approach to the remaining sub-modules including validation, i.e. plastics and buildings, plastics and vehicles, steel and buildings as well as steel and vehicles.
- Normalisation of trade flows between the EU-MFA and the REMIND MFA module as well as validation of results.
- Automated visualisation for all relevant results of the EU-MFA module.
- Final documentation reflecting all updates.

Beyond these technical updates, the EU-MFA module will be tested in a case study (see next sub-section),

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which includes the implementation of circular economy elements from Deliverable D3.5 ('*Open database of policies & technologies*'). The findings will be discussed with stakeholders, and their feedback will be considered for the final module version.

3.1.3 Requirements for the case study work in WP8

Within the case study, we aim to answer the following research question: "Which effect can circularity strategies have on EU trade flows and industrial resilience?". This research question originates from Deliverable D2.2 ('*Assessing Needs for Model Applications*') and was refined to allow testing of the core novelty of the EU-MFA module, namely the integration of top-down and bottom-up approaches. Moreover, it requires the implementation of circular economy elements from Deliverable D3.5 ('*Open database of policies & technologies*') in the EU-MFA module as well as the harmonisation of changing trade flows with the REMIND-MFA module. For the case study, we will analyse the individual effect of circular economy elements on material demand, secondary material availability and trade flows focussing on two cases, namely plastic packaging and passenger cars. To ensure the definition of relevant and feasible scenarios, stakeholder input was gathered during a workshop in December 2025. More details on the results of the workshop are provided in the report of Milestone 14 ('*Scoping research/policy questions*').

3.2 FORECAST-Sites

3.2.1 Updates from the initial model version

The first version of FORECAST-Sites was made available during the first project period. In the second project period we focused on adding further functionalities to the model and enable it to depict complex value chains with intermediate and byproducts.

The three key novelties are:

1. Consideration of process chains, including consideration of carbon capture.
2. Consideration of intermediate and side products that allows the consideration of complex process networks such as refineries and chemical industries.
3. Flexible investment decisions:
    - Option to reinvest in new process before the plant reaches its end of life.
    - Option to repair existing plants for additional cost.

Furthermore, we are rolling out further processes in base chemical industries, refineries and glass, paper and cement production.´The roll-out of the new optimisation approach as v2.0 will follow in the coming months in line with a planned publication.

3.2.2 Next steps towards the final module version

- Roll out new processes across industry sectors.
- Roll out new industry sites based on Fraunhofer ISI site database and dummy data where data is proprietary.

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3.2.3 Requirements for the case study work in WP8

- In the case study we focus on the RQ which is the optimal technology configuration and what infrastructure is required to decarbonize the cement, glass and paper industries in the basque country.
- The case study requires energy carrier price scenarios: for now, we will rely on simple assumptions for future energy carrier prices in Spain; in the future, inputs from OPEN-PROM could help FORECAST-Sites to have more realistic assumptions.

3.3 ITOM

3.3.1 Updates from the initial model version

Following the release of the framework code, initial sector modules, and comprehensive documentation in Deliverable D4.4, development has focused on enhancing data granularity and expanding functionality, particularly within the cement sector module.

Cement sector module:

- Site database update: Industrial site data has been updated to the Global Cement and Concrete Tracker (GCT) dataset. The database now encompasses 194 European clinker production sites, supplemented by specific research into kiln (oven) types and original construction years to better model replacement cycles.
- Announced industrial projects: The module now integrates announced industrial projects, including new kilns and Carbon Capture (CC) facilities. These projects are included in the site database and considered as installed capacities in the future years.
- Demand modelling granularity: To facilitate more precise model linking, the mapping of concrete applications has been expanded from four aggregate categories to 15 distinct application types. Every concrete demand category can be met with a unique combination of cement types.

All sector modules:

- Expansion of the mapping of CO_2 transport and storage with different storage clusters and cost trajectories. We now cover three aggregated storage clusters: North, South and Onshore. Every production site is mapped to have access to one or two of the storage clusters and different cost trajectories are used to differentiate between the future availability of CO2 transport and storage options.

3.3.2 Next steps towards the final module version

- Integrate scenario data according to the Scenario definitions in Transience.
- Remaining updates are still under definition.
- All sector modules are constantly updated by integrating new announced projects or updating the database in the case of site or plant closings.

3.3.3 Requirements for the case study work in WP8

- Tailor model scenario towards workshop needs.
- Include scenario assumptions according to the outcomes of the first workshop in Silesia.
- Set up output analysis for Poland and sites in Silesia.

3.4 LCA-TRANSIENCE

3.4.1 Updates from the initial model version

- Validation of the current data received from OPEN-PROM, FORECAST, and I-TOM. In addition, additional data requested from the MIC3 modules to further integrate the environmental LCA module with the MIC3 modules. Note that the current model is already functional with those MIC3 modules, and we are ready to integrate updates from the MIC3 modules in the next project phase.
- Two additional repositories were developed outside of the already functional environmental LCA module:
  - The first module is developed to provide more attention to climate-effective applications that may support industrial decarbonisation[8]. The code has been prepared for the following research paper: Terlouw, T., Moretti, C., Harpprecht, C., Sacchi, R., McKenna, R., & Bauer, C. (2025). Global greenhouse gas emissions mitigation potential of existing and planned hydrogen projects. *Nature Energy.* https://www.nature.com/articles/s41560-025-01892-9.
  - Secondly, another repository is developed to determine the climate effectiveness of the European Union Carbon Border Adjustment Mechanism (CBAM) for the global steel industry. Available via: https://github.com/tomterlouw/Steel_CBAM. This is used as the basis for the following research paper/preprint available at: https://www.researchsquare.com/article/rs-8099953/v1.
- Updated documentation on the environmental LCA module (see the GitHub repository).
- Internal discussions on how to link the novel regionalised LCA package (recently developed in 'edges'[9]) directly into the environmental LCA module. Further discussions are ongoing on how to better integrate circular economy measures to modify material requirements for the infrastructure used in background LCA databases.

3.4.2 Next steps towards the final module version

- Complete (non-proxy) energy system data from MIC3 modules (in IAMC format). Replacing proxy datasets with finalised energy system model outputs will enable more accurate modelling of environmental impacts across scenarios and sectors. The Environmental LCA module relies on substantial data requirements from MIC3 modules; hence, we are heavily dependent on them. Without harmonised input data—primarily regarding energy system model outputs and pathways—the LCA results may be less accurate.

[8] https://github.com/tomterlouw/hydrogen_applications.
[9] https://github.com/Laboratory-for-Energy-Systems-Analysis/edges

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- Harmonisation of input data from all output scenarios of MIC3 modules. This includes agreement on pathways, harmonisation of data formats, assumptions, temporal/spatial resolutions across the whole MIC3 framework.
- Possible assessment and potential integration of regionalised impact assessment methods to quantify location-specific impacts on water and biodiversity.
- Implement uncertainty analysis of markets relating to production mixes by considering various variations of such market mixes.
- Further discovering whether we can apply circular economy measures for industrial processes, buildings and infrastructure as an extension of the current simplified approach used.
- Further update documentation depending on the MIC3 model development next year.

3.4.3 Requirements for the case study work in WP8

- Together with Utrecht University, we are investigating the alignment between the Environmental LCA module and the case study for the Port of Rotterdam. Currently, the main limitation is that the Port's research question most likely requires an underlying energy-system model to quantify feedstock trade-offs and systemic interdependencies, given the complex energy ecosystem in the Port of Rotterdam. The LCA module alone cannot fully capture those interactions.
- We would likely require complementary energy-system outputs when applied to comprehensively consider the complex interactions of the energy system in the Port of Rotterdam. Without an energy-system model, any LCA contribution to the Port case would be a more simplified assessment.
- However, such constraints will likely not exclude potential contributions of the environmental LCA module to the case study of the Port of Rotterdam. There is also an option to support multiple case studies in a simplified way.

3.5 OPEN-GEM

3.5.1 Updates from the initial model version

- Determine / finalise the list of the key outputs of each model that will be used as input to another model.
- Prepare data exchange templates and harmonise the sectoral and regional concordance in each model soft linkage.
- Update modules to cover the soft-link approach.

3.5.2 Next steps towards the final module version

Next steps in WP4 deliverables correspond to the points above.

3.5.3 Requirements for the case study work in WP8

No points at this stage of the process.

3.6 OPEN-PROM

3.6.1 Updates from the initial model version

- Endogenisation of steam/heat prices.
- Improving the quality of input data.
- Inclusion of Direct Air Capture (DAC) technologies, and Carbon Capture and Storage (CCS) technologies in power generation, hydrogen, and industry sectors (preliminary).

3.6.2 Next steps towards the final module version

- Full integration in the main version of the model of the new iron and steel sectors with enhancement in technological decarbonisation option, integration of the most updated data of the steel production differentiated by route, steel demand projections in different scenarios according to the IEA World Energy Outlook 2023 and scrap availability.
- Integration of circular economy considerations across the iron and steel sector through proxies such as the amount of available scrap at country level under different level of recycling.
- Enhancement of the industrial module with representation for clinker and cement.
- Consistent with Task 7.2.

3.6.3 Requirements for the case study work in WP8

As the regional granularity of OPEN-PROM is on country level, OPEN-PROM will be paired with OPEN-GEM and the Rhine-Ruhr (North Rhine-Westphalia), and address the research question "Which effect can circularity strategies have on resilience and competitiveness of EU industries?" The objective is to model the impact of circularity measures, share of primary and secondary sectors using OPEN-GEM and harmonise activity of industrial sectors with OPEN-PROM. The focus will be on the chemical sector, i.e., primary and secondary plastics, and analyse separate scenarios to assess the impact on socioeconomic indicators and energy prices.

3.7 REMIND-MFA

3.7.1 Updates from the initial model version

Since the release of the first version of the REMIND-MFA, relevant progress has been made on following points:

- **Code documentation:** The REMIND-MFA is now documented in detail on readthedocs[10]. Large parts of the documentation are generated from the in-code documentation, such that the documentation is easy to maintain.
- **Open-source input-data generation:** Input data is processed with the open source mrmfa package[11] specifically developed for data preprocessing for the REMIND-MFA. The package consists

[10] https://remind-mfa.readthedocs.io/en/latest/
[11] https://github.com/pik-piam/mrmfa

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of R scripts which bring the raw data into the form that is used by the MFA, based on the MADRAT[12] package. Further, the input data is now versioned. This makes the full input data processing tool chain completely reproducible and transparent, starting at the raw data, the sources of which are given. Input data preparation steps include, for example, combining different data sources into one set, filling regional gaps, interpolating in time, if necessary, aggregation of country-level data into the REMIND regions, and formatting. All input data for the REMIND-MFA is now also available as open access on Zenodo, except for datasets prohibiting publication and redistribution.

- **Adding IAMC format export:** Export of output variables of the REMIND-MFA in IAMC data format is now enabled.
- **Implementation of scenario variations:** A scenario variation framework was implemented that enables simple variation of input parameters based on yml files. Different scenarios can now be defined as a set of input parameters that deviate from the parameters of the parent or baseline scenario. This enables running the MFA with scenario variations—such as circular economy interventions grouped into scenario narratives. The design allows new scenarios to be flexibly added and altered without knowledge of the source code.
- **Alignment of the code structure and methodology of the individual models:** The code structure of the individual models (cement, plastics, steel) has been aligned for better readability and to facilitate further model development.
- **Individual model improvements:** The individual models are under constant development, improving the model quality, detail, accuracy, and expanding their functionality. Since the release of the first version, the following improvements have been made:
  - Plastics:
    - Improvement of demand extrapolations: stock extrapolations are now performed separately for both good category and region.
    - Vetting of demand extrapolations by comparison with extrapolations from literature
  - Cement
    - Differentiation between cement and mortar.
    - Differentiation between different concrete strength types and mortar applications.
    - Representation of production and use losses.
    - Implementation of a detailed carbonation model simulating atmospheric carbon uptake in production, use and end-use stages.
    - Improvement of demand extrapolations: stock extrapolations are now performed separately for both stock type and region.

3.7.2 Next steps towards the final module version

The following steps are planned for the finalisation of the REMIND-MFA module in the second project phase:

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[12] https://cran.r-project.org/web/packages/madrat/index.html

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- **Expanding and improving the price-sensitive trade model:** The price-sensitive trade model is currently at an early stage. We will consolidate and further validate the trade module in the second project phase. This process is already started and currently ongoing.
- **Refining the input data:** We will replace global values with region-specific values where they are available.
- **Coupling and harmonising with the EU-MFA:** This entails harmonising all material flows between the EU-MFA and the EU region of the REMIND-MFA as well as coupling of trade flows.
- **Adding IAMC format reading:** This is a requirement for the coupling of the REMIND-MFA with other MIC3 satellite models, as input parameters from other models will be supplied in IAMC data format.

3.7.3 Requirements for the case study work in WP8

Within the case study, we will work together with the EU-MFA module to answer the following research question as mentioned above: "Which effect can circularity strategies have on EU trade flows and industrial resilience?". As we want to analyse changing trade flows with circularity interventions that will be implemented into the EU-MFA, the main requirements for the case study work are the consolidation and validation of the trade model in the REMIND-MFA and the harmonisation and coupling with the EU-MFA mentioned above.

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4 Towards integration to MIC3

This section presents current progress towards the integration of satellite modules to the MIC3 modelling framework. During the second semester of 2025, a methodology for model linking was elaborated by HOL, ICCS, Fraunhofer, and E3M partners, building on Deliverables D3.2 ('Open model development strategy')[13], D3.4 ('Framework for industry transition modelling')[14] and D3.8 ('Open science protocols')[15]. Additionally, all modelling teams were asked to provide a list of data inputs that their module will need from the other TRANSIENCE modules in order to prioritise and plan model linking. Both the methodology and the list of data inputs were extensively discussed by all partners during the project's General Annual (GA) meeting in Brussels in December 2025. The following needs have emerged through this discussion:

1. **Develop a database for harmonised common assumptions**: While the satellite modules of TRANSIENCE can capture a wide variety of activities related to industrial transformation, some modules require exogenous inputs that are not provided by any of the project's modules. Among the parameters that have been already identified are biomass availability, taxes and subsidies for energy carriers, and production costs (shadow prices). These parameters will be provided through an external database that will keep all harmonised common assumptions of the MIC3 modules.
2. **Create a basic workflow to test MIC3**. The order in which models are run depends on the question they need to answer. Nevertheless, many modelling partners suggested that a basic workflow for running the models will be needed to initialise the connections between them. For this, the workflow for examining economic implications of successful high R-strategies from the Deliverable D3.4 was adapted by removing all feedback loops and keeping a simple, linear structure (Figure 1). This will be further adjusted in the coming months based on the needs of data linking. Additionally, one additional workflow is envisioned to be tested in the context of Task 7.6 ('Integration of economic aspects into MIC3'), examining the impact of high energy prices as an incentive for industrial transformation (e.g., by looping between OPEN-PROM and the industry models).

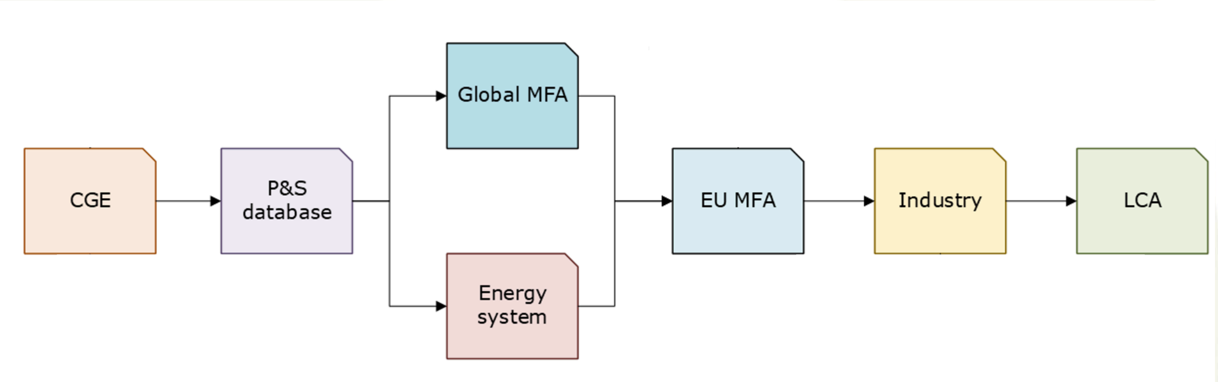

Figure 1. Basic module workflow for testing interconnections in MIC3 (adapted from Deliverable D3.4).

[13] https://doi.org/10.5281/zenodo.14034438
[14] https://www.transience.eu/sites/default/files/2025-07/D3.4%20Framework%20for%20industry%20transition%20modelling%20v1.00_SUBMITTED.pdf
[15] https://doi.org/10.5281/zenodo.17349954

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3. **Prioritise data exchange needs**:
    - Production/consumption activity, e.g. packaging demand (Source: OPEN-GEM, Sink: EU-MFA, FORECAST)
    - Energy carrier costs, generation availability (Source: OPEN-PROM, Sink: ITOM, FORECAST)
    - CO_2 price trajectory (Source: OPEN-GEM, OPEN-PROM, or Assumption, Sink: ITOM, FORECAST)
    - Trade flows harmonisation (Between OPEN-GEM and REMIND-MFA)
4. **Check model outputs for consistency**: As each module uses its own modelling paradigm and solution method, it is expected that some of their outputs may not fully align with each other. For instance, energy demand for industry is calculated by both OPEN-PROM and ITOM but it is not expected to be the same. Nevertheless, under the same driver (e.g., increased energy prices), both models should show similar trends (e.g., decreased energy demand). To ensure consistency between models, validation routines will be developed in the context of Task 7.4 ('Ensuring compatibility of sectoral model results with, and feeding into, the IPCC AR7 cycle') and Task 7.5 ('Integration of modules into MIC3').

The following sub-sections show the current version of the linking methodology and input data requirements for each module. The methodology will be further refined within 2026 while the inputs will be documented in detail in the context of Deliverable D7.2

4.1 MIC3 linking methodology

- **Identify assumptions and epistemic foundations between models.**
    - Assess incompatibilities between the models such as in terms of their regional mapping (e.g., EU may be EU27 for one model and EU28 for another).
    - Determine the main data categories that will be exchanged.
- **Identify inputs and outputs for each model.**
    - Check which data format is used for input and output (ideally, all models should use the IAMC format).
    - Assess whether we need to harmonise or in any way adapt a model output before using it as another model's input.
    - Reconcile the sectoral, spatial, and temporal granularity of the models (downscale or upscale).
    - Identify issues with proprietary data and find open access proxies that can be used instead.
- **Establish manual soft linking**
    - Develop a conversion script for updating the outputs of the first model as inputs for the second
    - Run the first model, produce an output (e.g., in csv form), share it with the second modelling team, run the conversion script to update the input file of the second model, and then run

the second model.

- For the first runs, try to exchange just a couple of variables. Then create a simple but more realistic case study where all required variables are exchanged.
- Fix bugs in the linking, evaluate the validity of results through simple testing (e.g., values are within expected bounds etc.).

- **Automate linking**
  - Assess whether models need to run in the servers/computers of their organisations or they can also run autonomously on a server. Understand and evaluate computational needs.
  - Create an automated workflow based on the manual linking (e.g., automatically upload model outputs on a server, run the data conversion links, and create the inputs for the other models)
  - Create an orchestrator application that will manage the workflow between the models, monitor the linking, show errors, etc.

4.2 Required inputs per module

4.2.1 EU-MFA

Table 2. Data required by EU-MFA from other modules or the assumptions database

Input required	Sub-module	Source	Description	Adaptations needed
Material intensity buildings	Buildings	P&S Database	No data manipulation required as database differentiates three climatic regions and several age cohorts	-
Population	Buildings	OPEN-GEM	Differentiated by member state	-
Per capita stock	Buildings	P&S Database	Used to calculate total residential stock per member state	-
Residential share	Buildings	P&S Database	Determines share of single-family and multi-family houses	-
Commercial change	Buildings	P&S Database	Determines changes in the commercial building stock by year and member state	-
Building inflow	Buildings	P&S Database	Determine building inflow from the building stock and building outflow	-
Building outflow	Buildings	P&S Database	Determine building outflow from the residential per capita building stock, share of residential building types, population development, changes in the non-residential building stock and the non-residential building stock in a base year	-
Material intensity vehicles	Vehicles	P&S Database	No data manipulation required as database differentiates different vehicle types and sizes	-
Share of vehicle sizes	Vehicles	P&S Database	Used to assign different vehicles sizes to vehicle inflow	-
Vehicle registrations	Vehicles	OPEN-PROM	Differentiate the vehicle inflow to consider different vehicle sizes, already considers varying vehicle types	-
Consumption change	All	OPEN-GEM	No data manipulation required, has to differentiate various use sectors	-
Translation	All	P&S Database	No data manipulation required, has to differentiate different materials and use sectors	-
Production from	Plastics	OPEN-GEM	Harmonisation of overall trend for	-

Plastics-products primary			converter demand	
Production from Plastics-products secondary	Plastics	OPEN-GEM	Harmonisation of overall share of mechanical recycling	-
Intermediate consumption from both sectors "Production of plastic products"	Plastics	OPEN-GEM	Harmonisation of trends for converter demands by sector of application	-
GDP	All	OPEN-GEM	Can be used as an overarching driver if finer correspondence between sectors is not possible	GDP is the fallback option to calculate material quantities (e.g., for packaging). Would need to be discussed further by the modelling teams.
Trade	All	REMIND-MFA	Mapping of product categories required	-
Consumption	All	OPEN-GEM	Household consumption, investment, government expenditures	Focus here more than the activity. An alternative, if you go to production, is to keep it aggregated.

4.2.2 FORECAST-Sites

Table 3. Data required by FORECAST-Sites from other modules or the assumptions database

Input required	Source	Description	Adaptations needed
Energy carrier cost	OPEN-PROM	Defines the price path per energy carrier and country/region; key energy carrier: electricity, hydrogen, natural gas, oil, biomass, plastic waste.	The OPEN-PROM team will check whether this can be provided.
Energy carrier subsidies	Assumptions database	Energy carrier subsidies (e.g. through policies) per energy carrier and country/region	-
Energy carrier taxes	Assumptions database	Energy carrier taxes (e.g. through policies) per energy carrier and country/region	-
Region energy carrier availability	OPEN-PROM	Availability per energy carrier per region/country – for example for biomass	Waste flows can come from EU-MFA. Other energy carriers can come from OPEM PROM.
Region energy carrier availability (only waste)	EU-MFA	Availability per energy carrier per region/country – for waste for recycling	-
Production activity	EU-MFA	Defines the assumed development of production quantity per product and country/region/site	-
Production activity	OPEN-GEM	Defines the assumed development of production quantity per product and country/region/site	There is a good representation of industries in OPEN-GEM (e.g., fertilisers, cement, aluminium, etc.) - including also recycling options in some cases. OPEN-GEM activity is in monetary values but can be translated to production activity in terms of mass by using a base year where the mass values are known and then adapting them based on the growth values from OPEN-GEM.
Policies (CO_2 price)	Assumptions database	Defines CO_2 price path according to EU-ETS definition	-
Product price	Assumptions	Cost of products on international market can	Currently unknown whether it can

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	database	drive production or check whether production is competitive	be provided by any model, it can be potentially part of the common assumptions database.

4.2.3 ITOM

Table 4. Data required by ITOM from other modules or the assumptions database

Input required	Sub-module	Source	Description	Adaptations needed
Energy Cost	All	OPEN-PROM	Yearly and per country cost data for relevant energy carriers (e.g. electricity, hydrogen, natural gas)	Hydrogen is currently in one category (not green, grey, etc.). It can be provided per country. All other carriers are assumed to be easy to transfer.
Biomass availability	All	Assumptions database	Yearly and per country data on biomass availability for industrial use	We can have an exogenous assumption on what is the same maximum potential on biomass. It should be harmonised between OPEN-PROM, ITOM, FORECAST-SITES and other models. We can also use another model beyond the project to get biomass availability, e.g., GLOBIOM[16].
ETS Price	All	OPEN-GEM, OPEN-PROM, assumptions database	Yearly CO_2 price development	Scenario-specific, it can be both an input (if the idea is to calculate emissions) or an output (if the emissions target is the starting point).
Availability of refinery products	PetChem	OPEN-PROM	Yearly production of refinery products, esp. naphtha	OPEN-PROM is working on getting data for refineries. However, they are currently very aggregated. Kassel colleagues will also work on integrating refineries in ITOM-petchem in Phase 3 of TRANSIENCE.
Plastics production	PetChem	EU-MFA	Yearly converter demand of polymers	-
Concrete production	Cement	EU-MFA	Yearly production of concrete by sector of application	-
Cement production	Cement	EU-MFA	Yearly production of cement	-
Steel scrap	Steel	EU-MFA	Yearly availability of steel scrap for potential recycling, incl. scrap quality	-
Plastic waste	PetChem	EU-MFA	Yearly availability of sorted plastic waste, by polymer and origin application	-
Recyclates	All	EU-MFA	Yearly availability of secondary material	-

4.2.4 LCA-TRANSIENCE

Table 5. Data required by the LCA-TRANSIENCE module from other modules or the assumptions database

Input required	Source	Description	Adaptations needed
Technology production mixes electricity, cement, steel, transport	OPEN-PROM	Production mixes for electricity, cement, steel, transport (passenger car, bus, train, truck, two-wheeler), needed to modify these production mixes in the background LCA database.	electricity, steam, hydrogen are already possible. E-fuels will come in the future.

[16] https://iiasa.ac.at/models-tools-data/globiom

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Final energy demand by pathway/route	OPEN-PROM	All final energy demand variables for each scenario, needed to quantify environmental burdens of entire energy system transformation pathways.	-
Technology production mixes cement, steel, petrochemicals	ITOM	Production mixes for cement, steel, and (potentially) petrochemicals.	For cement and petrochemicals, LCA does not have yet results from ITOM (so to develop the appropriate inventories). For Steel they have but can be updated. ITOM will share the technology routes they have.
Cumulative deployment and specific energy use	OPEN-PROM	Specifications for Direct Air Capture (solid sorbent or liquid solvent)	OPEN-PROM team will check if it is possible to distinguish between solid sorbent and liquid.
Final energy demand by pathway/route	ITOM	All final energy demand variables for each scenario, needed to quantify environmental burdens of entire industrial-specific energy system transformation pathways.	Need both aggregated and specific energy demand (the aggregated one can come from OPEN-PROM). Need also the assumptions. Better to have pathway specific assumptions e.g., how much steel is produced with DRI to calculate toxicity.
Efficiency	OPEN-PROM, FORECAST	Efficiency of electricity generators and fuel production pathways	What is currently available is the efficiency of plants producing electricity (depending on learning curves).
Technology production mixes fuels and steel	FORECAST	Market mixes for steel (maybe not needed though as we already use them from ITOM) and a wide set of fuels: 1) hydrogen (comes from OPEN-PROM), 2) methanol, 3) ammonia, 4) petrol, biodiesel, and diesel, 5) bioethanol, and others. These are needed on spatially-explicit data that we may aggregate (from FORECAST, we do this already for ammonia and methanol mixes).	Some of them can also be exogenous. Some can be potentially come from FORECAST (e.g. bioethanol).
Technology production mix biomass	Assumptions database	Specifically, we need biomass crops – purpose grown, biomass wood – purpose grown, and biomass – residual.	Harmonised assumption across models.
Recycling shares	EU-MFA, ITOM	Recycling shares of metals (primary vs secondary), for example aluminium, copper, chromium, cobalt so that we can further modify our LCA background LCA database based on this.	OPEN-GEM may not be the most suitable model. EU-MFA or ITOM may be better. Aluminium, copper, chromium, cobalt cannot be calculated endogenously, they should be exogenous assumption (check if they exist in OPEN-GEM). Chromium can be potentially associated with steel (their recycling rates are common with steel)

4.2.5 OPEN-GEM

Table 6. Data required by OPEN-GEM from other modules or the assumptions database

Input required	Source	Description	Adaptations needed
Fuel mix	OPEN-PROM	Used to calibrate the parameters in CES - %	-
Investments	Assumptions database	Investments to build the capacity for the transformation [Monetary]	Initially it was mentioned that it could come from ITOM. However, investment is not annualised in ITOM. Potentially, it can be discounted to the first year, but it would then be mostly the same across scenarios. Ideally, investments can be shared technology assumptions.
Production structure	ITOM/FORECAST	Used to calibrate the parameters in CES. We need this in order to harmonize the capital cost, labour cost, energy cost by type of fuel,	-

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		material cost by type of material, Services cost. The higher detail possible the better. [%]	
GHG emissions target/or carbon price	Assumptions database	Either emissions target or carbon price for the scenarios run is required. [tCO2eq or USD/tCO2]	-
GHG emissions target/or carbon price	OPEN-PROM	Either emissions target or carbon price for the scenarios run is required. [tCO2eq or USD/tCO2]	-
Emissions or emission intensity	OPEN-PROM	To harmonize the emission intensities of the sector. [tCO2eq]	-

4.2.6 OPEN-PROM

Table 7. Data required by OPEN-PROM from other modules or the assumptions database

Input required	Source	Description	Adaptations needed
Macroeconomic factors	OPEN-GEM	GDP, population, household income, industrial activity.	-
Final industrial demand by carrier	ITOM/FORECAST	The energy demand by carrier for the industrial sectors (for each subsector).	This input can come from the industrial models, and we will then check if we need to rerun OPEN-PROM. So potentially it would require a loop. If not, it can be a static assumption from the database.
Technology (production) mix of industrial sectors	ITOM/FORECAST	The production structure of the industrial sectors and the shares of technologies used (for each subsector). Different technology routes.	
Prices of materials	Assumptions database	Prices of key materials (e.g., steel, cement) to adjust technoeconomic assumptions	Potentially translate energy assumptions (e.g., how much PV would grow across the EU) and translate them to material use.

4.2.7 REMIND-MFA

Table 8. Data required by REMIND-MFA from other modules or the assumptions database

Input required	Sub-module	Source	Description	Adaptations needed
GDP	All	OPEN-GEM	As an overarching driver for consumption if EU material stocks are to be extrapolated within REMIND-MFA	-
Trade flows	All	OPEN-GEM	For harmonisation of trade flows between OPEN-GEM and REMIND-MFA	REMIND-MFA has detailed trade for some sectors. The translation between monetary values and volumes can happen through the growth rate: have volumes for a base year and then use growth rates from the monetary values.
Domestic demands and other parameters	All	EU-MFA	For harmonisation of flows between EU-MFA and EU region in REMIND-MFA	We would need to harmonise between the different regional disaggregations of the modules (i.e., EU28 vs. EU27+3).
Production costs (shadow prices)	All	ITOM	eventually for calculating price-sensitive trade (currently planned to use prices from REMIND)	These are mostly for comparing scenarios, it needs to be checked if they are used as production costs. Alternatively, we can use REMIND here to get the prices. It can a be a deep dive for D7.6.

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