TRANSIENCE

TRANSITIONING TOWARDS AN EFFICIENT, CARBON-NEUTRAL CIRCULAR EUROPEAN INDUSTRY

Date: 30/10/2024

D3.2 – Open model development strategy

WP3 – Characterising circularity and decarbonisation opportunities – generating model inputs

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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	Eskarne ARREGUI PABOLLET				
Project Coordinator	Institute of Communication and Computer Systems (ICCS)				
Deliverable	D3.2 – Open model development strategy				
Work Package	WP3 – Characterising circularity and decarbonisation opportunities – generating model inputs				
Date of Delivery	**Contractual**	31/10/2024	**Actual**	30/10/2024	
Nature	Report		**Dissemination Level**	Public	
Lead Beneficiary	Utrecht University (UU)				
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Keywords	Model development strategy, open science, stakeholder engagement, circular economy, industrial transformation policy, data exchange				

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 deliverable is intended for the broader stakeholder community of TRANSIENCE, including policymakers and other IAM-related projects, to provide an overview of the planned capabilities of MIC3 and the modules comprising it, of how development is influenced by stakeholder insights, as well as of our overall approach towards modelling decarbonisation vis-à-vis circularity performance. It is also intended for the IAM scientific community to present the added capabilities, expansions and integrations that are planned and performed in the project.

3. Short summary of results (<250 words)

This report outlines the development strategy for the MIC3 modelling framework, which aims to simulate European industry's circular economy and climate change mitigation efforts. The report leverages findings from previous research and stakeholder workshops to inform the strategy. It proposes a scheme for the development of MIC3's individual modules, including data exchange protocols, and explores the challenges of integrating circular economy and decarbonisation measures into a large, interconnected model ecosystem. The report also analyses existing policies and strategies related to the circular economy in three focal sectors: steel, cement, and plastics, highlighting both progress and gaps in integrating decarbonisation and circular economy initiatives. It then concludes by outlining a five-step open model development strategy for MIC3, emphasising the importance of iterative development and collaboration with stakeholders.

4. Evidence of accomplishment

This report.

Preface

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

ICCS – Institute of Communication and Computer Systems	EL
CEPS – Centre for European Policy Studies	BE
E3M – E3-Modelling AE	EL
Fraunhofer – Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.	DE
HOL – HOLISTIC IKE	EL
PIK – Potsdam Institut für Klimafolgenforschung e.V.	DE
PNTEC – Park Naukowo-Technologiczny Euro-Centrum Spolka Z Ograniczona Odpowiedzialnoscia	PL
TECNALIA – Fundacion 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 outlines a strategy for developing an open model framework, called the Model for European Industry Circularity and Climate Change mitigation (MIC3). The components comprising this framework are being developed during the first phase of the TRANSIENCE project, while their integration into the MIC3 fully integrated ecosystem will be completed during the second phase. The goal of this framework is to allow modelling in-depth pathways to achieve carbon-neutral, circular, and sustainable European industries.

The report draws on three main areas of work to inform the model development strategy. First, it examines the existing capabilities of individual modelling modules that are part of the TRANSIENCE project; the modules will eventually be integrated into the MIC3 framework. This analysis identifies gaps in the modules' abilities to incorporate circular economy (CE) strategies, particularly concerning their interaction with decarbonisation efforts.

Second, the report considers stakeholder perspectives from industrial regions in Europe. Workshops held in the Basque Country (Spain) and the Rhine-Ruhr Area (Germany), which were held early as part of the two corresponding lighthouse case studies, revealed that, despite strong interest in CE and decarbonisation, stakeholders have specific concerns that they would like addressed by MIC3. These include concerns about geopolitical developments, urgent investment backlogs, and cross-sectoral network (dis)advantages.

Third, the report reviews existing and developing EU policies related to CE in three key sectors: steel, cement, and plastics. While there has been progress in developing CE policies, particularly in product regulations, the report notes a lack of integration between decarbonisation and CE interventions. Key lessons from this review are highlighted for consideration in the development of new modelling capabilities.

The report then summarises hitherto progress on the coupling and data flows of MIC3 modules. To ensure the smooth exchange of data between modules, the project will utilise the IAMC data template, a widely used standard for model intercomparison that promotes data consistency across all modules—also used in the IPCC WGIII scenario submission process. The report also provides a baseline modelling workflow that is adaptable to research questions, thereby providing a solid basis for model development.

Finally, the report proposes a five-step open model development strategy that focuses on the successful alignment of the previously discussed stakeholder needs, policy ambitions, and model development:

- Distil key industry, policy, and other stakeholder insights into specific research objectives.
- Refine model couplings and data exchange interfaces based on these research objectives.
- Construct a comprehensive set of CE and decarbonisation measures that can be incorporated into MIC3.
- Develop the individual, open-source modules of the MIC3 model ecosystem, ensuring their easy accessibility.
- Define and agree upon basic scenario narratives for shaping the model use cases.

The report stresses that the model development process will be dynamic and iterative, adapting to new information and insights as the project progresses.

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1 Introduction

The first phase of the TRANSIENCE project focuses on laying the groundwork for the Model for European Industry Circularity and Climate Change mitigation (MIC3) modelling framework. Various work packages have been contributing valuable insights into both the capabilities of the constituting modules as well as the pressing needs of industrial, policy and other stakeholders.

The aim of this report is to review the relevant work conducted thus far and, based on the insights gained, formulate an open model development strategy for MIC3 with focus on the development during the first phase of TRANSIENCE (M1-18). Aligning the vast amount of identified knowledge gaps with innovative model development will be an iterative process throughout the rest of this phase. This strategy offers informed guidance for *how* this process should be most optimally organised. Figure 1 provides a conceptual overview of how past and ongoing activities have informed the creation of this strategy. The report itself is structured accordingly.

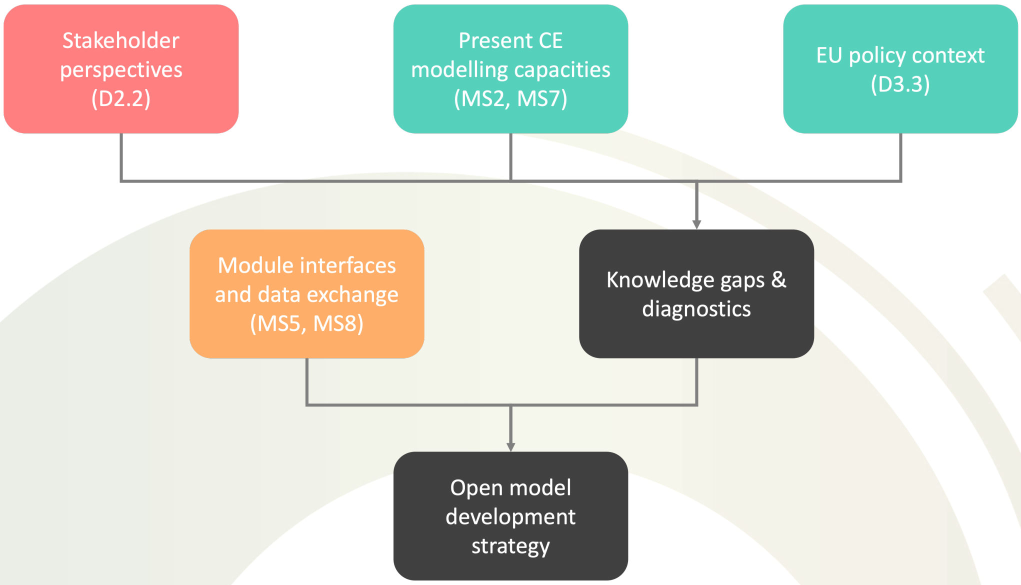

Figure 1. Schematic representation of the inter-relation of TRANSIENCE works in informing the open model development strategy proposed in the present report (red: WP2, green: WP3, orange: WP4).

Sections 2-5 offer insights from three parallel streams of work that informed the model development strategy by helping to identify knowledge gaps and diagnostics for model improvement. Section 2 reviews the investigation into current capabilities of models that participate in TRANSIENCE (and will be later integrated into the MIC3 model) in addressing circular economy (CE) strategies in the context of decarbonisation transition, highlighting existing gaps that need to be addressed in the model's further development. Section 3 summarises stakeholder perspectives from different European industrial regions, including the main drivers and barriers to decarbonisation and circular economy transitions. These insights are crucial to ensuring that MIC3 is responsive to stakeholder needs. Section 4 examines the latest developments in EU circular economy policies and their implications for three focal sectors: steel, concrete, and plastics. Section 5 then offers an overview of the latest progress on module interfaces and the protocols for data exchange.

Finally, Section 6 presents the open model development strategy derived from the lessons learned throughout the first phase of the project. The current strategy reflects the status-quo of the MIC3 model

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development. The implementation of this strategy should take into account the future development in TRANSIENCE. It encourages the project team to iteratively adapt the scope as new information becomes available.

2 Overview of individual modules: how circular economy measures could be modelled

2.1 Circular economy strategies

To date, there is not a universally agreed definition of the circular economy. Scholars and practitioners have so far put forward over one hundred different formulations (Kirchherr et al. 2017; Kirchherr et al., 2023). The way definitions conceptualise the circular economy usually depends on the perspectives (e.g. policy targets and industrial transition ambition) and the specific context (e.g. a specific category of products value chains). In May 2024, ISO 59004 proposed a definition of circular economy which was articulated by a broad range of societal stakeholders. TRANSIENCE adopts the ISO definition of circular economy as the starting point to incorporate CE strategies into the MIC3 framework.

"Circular Economy is an economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development"

--- ISO 59004:2024

The four fundamental CE strategies of managing circular flow of resources are identified: 1) narrowing, 2) slowing, 3) closing and 4) substitution[1]. Table 1 shows their definitions and the related 'R-strategies', often seen in practice. When incorporating CE measures into MIC3, the framework will follow the structure of these four basic CE strategies. The MIC3 framework will integrate various satellite modules focused on socio-economic, techno-economic, material flow, energy system planning and environmental impacts of a circular economy. The network of the modules offers the opportunity to understand the potential socio-economic and environmental trade-offs and co-benefits when specific CE strategies are implemented.

The "Narrow" and "Slow" measures are often considered as prioritised CE strategies that could lead to direct decrease in the final material demand and therefore lower energy and resources demand for the society as a whole (Wiedenhofer et al., 2024). The "Close" and "Substitute" measures often require the adoption of new technologies, which lead to additional demand in energy and resources (e.g. recycling) or an increase in alternative feedstocks (e.g. bio-based). For most measures, the macro-level, quantified trade-offs in both environmental and economic terms are not yet clear.

Table 1. The four basic CE strategies adopted in TRANSIENCE, their definitions, and the related R-strategies.

Basic CE strategies	Definitions	Expected consequences	Related R-strategies (Potting et al., 2017)
Narrow	Minimal use of energy and materials, including both	Low energy and material demand	Refuse, Rethink, Reduce

[1] For a detailed description and implementation see, for example, the Dutch National Circular Economy Programme 2023-2030. https://www.government.nl/documents/reports/2023/09/27/national-circular-economy-programme-2023-2030

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	efficiency and sufficiency measures		
Slow	Use the in-stock material as long as possible	Low energy and material demand. The economic trade-offs be significant, e.g. growth in the service sectors	Reuse, Repair, Refurbish, Remanufacture, Repurpose
Close	Use the secondary materials instead of primary ones	Reduction of primary resources with expected environmental and economic trade-offs	Recycle, Recover
Substitute	Use of alternative feedstock, either for higher cycling potential (e.g. bio-based) or safer return to the biosphere	Reduction of (conventional) primary resources and increase in production of alternative feedstock, with expected environmental and economic trade-offs.	Not applicable

2.2 A first inquiry into satellite module capacities to accommodate CE strategies

In TRANSIENCE, each module will be connected to the broader MIC3 framework, enabling the integration of CE strategies at different stages of a product/material life cycle, from production to end-of-life waste management. The four identified CE strategies are highly generic, with the intention to be used in different contexts, with our goal focusing on operationalising said strategies within the development of our modules and the overall MIC3 modelling framework. As a first attempt to map out modules' detailed capabilities in the context of CE, we chose to evaluate the value chain of cement and concrete because of its relative simplicity. We identified 10 CE measures ranging from reducing over-specification to introducing innovative cement types (see Table 2). For each module we identified how these measures could be modelled in different life cycle stages in the concrete supply chain, as reflected in their current module capacities, and including associated data requirements.

Table 2. Ten CE measures reported in literature for the concrete value chain

CE strategy		CE Measures identified by academic and industrial assessments
Narrowing	S1	Avoid over-specification
	S2	Prefabrication: Lightweighting
	S3	Greater utilisation of buildings
	S4	Optimisation of binder intensity
Slowing	S5	Renovation (structural, deep, or light)
	S6	Reuse of building elements
Closing	S7	Recycling of concrete
Substitution	S8	Clinker substitution
	S9	Innovative cement types
	S10	Timber in place of concrete

A short summary of this exercise is presented below:

- **EU-MFA** (European Material Flow Analysis): This module tracks material flows within Europe, focusing on sectors like buildings and infrastructure. It can model the CE strategies related to process parameters (e.g., clinker substitution), building archetypes, and material intensities. In theory, all 10 measures can be modelled. A strong focus will be made in the 'use phase' of concrete, i.e., the demand and the stock development.

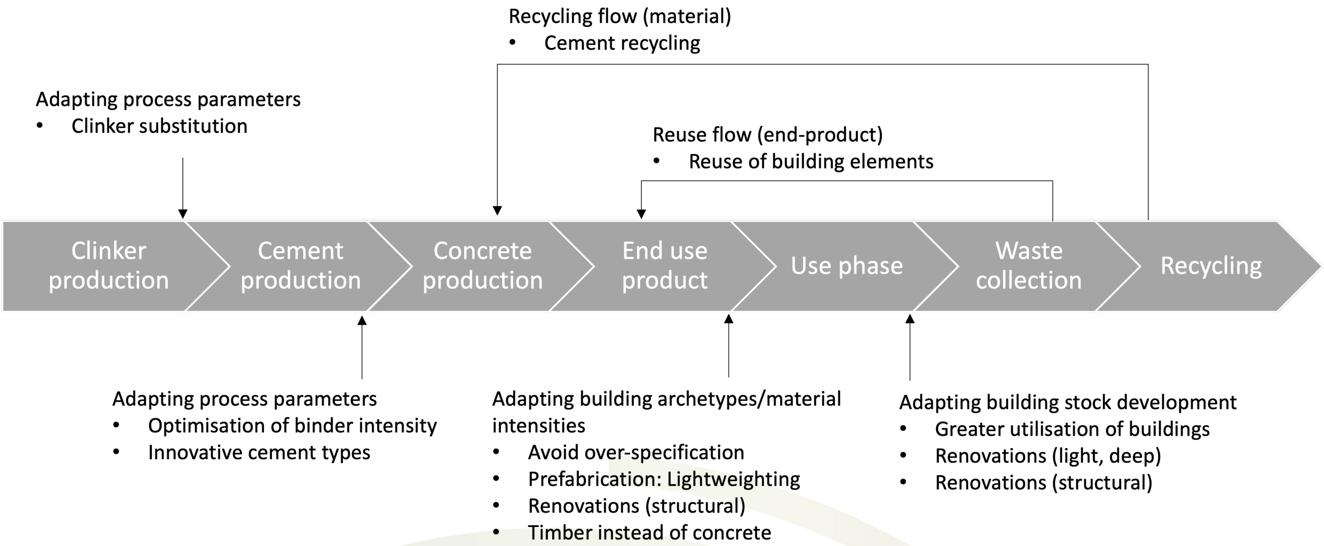

Figure 2. Modelling of the selected CE measures for the concrete value chain in the EU-MFA module

- **SIMSON** (Global Material Flow Analysis): Similar to EU-MFA but applied globally. It focuses on the global cement and concrete flows, adapting CE strategies for different world regions based on material availability, demand and costs.
- **EDM-Invest** (Techno-Economic Module): This module will have a strong focus on the production phase of cement and concrete. It is an industry-oriented model. It could simulate clinker substitution and innovative cement types, accounting for regional material availability and costs. The S8 and S9 measures can be directly modelled, whereas S1-6 and S10 can be modelled as the results of demand change from other modules, e.g. EU-MFA or SIMSON.
- **FORECAST-Industry** (Techno-Economic Module): This module represents energy demand and production costs in Europe's heavy industries. Like the EDM-Invest, the FORECAST model could focus strongly on the "Substitute" CE measures (S8-9) related to clinker substitution, innovative cements, and recycling, focusing on energy efficiency in cement production. The other CE measures (S1-6 and S10) can be driven by the change in the final demand modelled by other modules such as the MFA modules.
- **Premise** (Life Cycle Assessment Module): This module assesses the cradle-to-grave environmental impacts of concrete production. In the example of concrete, it is possible to factor all 10 CE measures. The Premise module could be driven by MFA and energy modules to project the life cycle environmental impacts of a CE measure.
- **OpenGEM** (Macro-economic CGE model) and **OpenPROM** (Energy system simulation model) could function in two ways: 1) they set the boundaries of MIC3 and define the socio-economic and energy transition developments (including energy and CO_2 prices) for the other modules; or 2) they receive the feedback from individual modules (or combination of modules) in order to project the CE

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measure-induced socioeconomic changes.

To conclude this exercise, for each individual module, a wide range of CE measures can be modelled, offering great capabilities in MIC3. However, we also see **key challenges** when translating CE measures into a large, interconnected model, in particular:

How (and where) endogenous CE measures could act as a driving force in MIC3. The interactions amongst modules in MIC3 need to be further refined with a specific context.

The development of MIC3 has been so far oriented towards the interactions amongst energy-material-environmental impacts, but not the impacts on the socio-economic changes. This can be highlighted for the two highly prioritised CE strategies, namely, Narrow and Slow. Both strategies are expected to lead to a lower energy and material demand (and therefore a lower environmental impact). However, it is not clear to what extent the economic implications could also be captured by MIC3, for example, in case of increased reuse and repair, the demand from the industrial sectors is expected to decrease while service sectors will likely grow. A clear scoping effort is required. See further discussion in Section 4 for the specific sectors.

3 Needs from the industrial sectors

To ensure the relevance and applicability of our modelling efforts to real-world challenges, TRANSIENCE has implemented a stakeholder engagement strategy focussing on regional industrial clusters. Industrial systems are often regionally clustered. Clustering creates opportunities but also challenges for decarbonisation, circularity and sustainability. A place-based approach provides conceptual and methodological tools for guiding industrial decarbonisation in ways that are grounded in the social sciences. Yet, current models typically do not adequately reflect the complex interactions happening at the regional level.

By the preparation of this report, two regional stakeholder workshops had been conducted and analysed in the Rhine-Ruhr Area in Germany and the Basque Country, Spain. These workshops aimed to foster a more inclusive dialogue, identify specific needs and gaps in existing models, and co-create actionable solutions. By engaging with a diverse range of stakeholders, including policymakers, industry representatives, and civil society organisations, we sought to enhance the legitimacy and validity of our research. This section will highlight some preliminary insights with the intention to inform model development and scenario work. A more elaborate synthesis of the findings will be prepared separately as D2.2.

3.1 Insights from the Basque Country Regional Stakeholder Workshop

Based on the discussion with local stakeholders, the following concerns regarding Basque industry decarbonisation and circularity arose during first regional workshop of TRANSIENCE. Basque industry aims to become carbon neutral, more circular and sustainable in the long-term horizon. Nevertheless, to meet these ambitions some challenges have to be tackled.

On the one hand, current fossil dependency can be phased out through the electrification (based on renewable electricity generation) of industrial processes and the use of green hydrogen or other alternative fuels (e.g. methanol, ammonia, biofuels, or synthetic fuels) in specific hard-to-abate industries. The former requires accurate planning for grid expansion, while the latter solution is still subject to debate given current technical and economic barriers. Concerning also the decarbonisation aspect, CCS was also mentioned as a solution to reduce process emissions, although its deployment was only perceived as a viable option for certain industries.

On the other hand, alongside efforts toward decarbonisation, stakeholders emphasised the need to improve circularity in the Basque industry. This includes promoting secondary markets, exploring synergies between industries and other sectors, and making recycling and material reuse mandatory through coordinated regulation. Ecodesign and life cycle analysis (LCA) should be taken into account, and it's important to assess scope 3 emissions and the impacts of critical raw materials (CRM). Material availability remains a concern, especially given its geopolitical implications and the complexity of global supply chains. To tackle both decarbonisation and circularity, stakeholders highlighted the importance of collaboration between public and private sectors, a stable and coherent regulatory framework, and the promotion of local symbiosis between urban and industrial areas.

To overcome these challenges, prospective assessment through comprehensive and holistic modelling of the industry is key to support the design of industrial transition strategies. Regarding **the needs and gaps** to be covered by modelling tools (and MIC3 in particular), the stakeholders highlighted the following suggestions:

- Supply infrastructure (transport and storage) should be considered.
- There is a potential value for GIS modelling to identify resources and synergies.
- CO_2 emissions from processes should be considered, to holistically evaluate CCS/U solutions
- Qualitative aspects (e.g., social, health concerns, externalities) should be considered in modelling
- Small and Medium Enterprises (SMEs) should be considered in the transformation of industry, and we should also model/evaluate how the transition will affect them.
- A rigorous quantification of impacts should be advanced, including the allocation of responsibilities among companies, government, etc. LCA should be included in models, evaluating scope 3 emissions and the impact of CRM requirements.
- Social aspects should be integrated: How to evaluate social acceptance of decarbonisation/circularity projects in industries/companies/society? How to evaluate societal awareness when looking at reconditioned products? Furthermore, the use of traditional drivers like GDP, prices/costs, exogenous demands, may be supplemented or replaced by more sophisticated approaches based on behavioural components, societal aspects, companies' strategy-making (e.g. agent-based modelling).

Altogether, stakeholders recognised the relevance of modelling tools. On this matter however, two difficulties arise. On the one hand, data is not often available with the required granularity or robustness, therefore detailed data is required from different industries, markets, and scales. Indeed, if companies should be asked to provide data, models should return useful insights and evaluations for their businesses. On the other hand, aligning stakeholder interests will be a difficult task since:

- academics are pushing for open-source modelling work; and
- regional clusters are asking help for specific problems from their participating companies, while perceiving the results from models as more relevant for governments.

Thus, regional agencies saw the potential in modelling initiatives such as MIC3 but were reluctant to participate actively at this stage. They mostly expect interesting ad hoc results and useful analysis that answers their specific questions rather than a more general discussion.

3.2 Insights from the Rhine-Ruhr Area Regional Stakeholder Workshop

In the Rhine-Ruhr region a healthy discourse on industrial transformation has been ongoing for several years. A key driver for this was the NRW (North Rhine-Westphalia) state government's IN4climate initiative, a platform for bringing together government, key industrial stakeholders, especially from the state's strong energy-intensive industry base, and scientific actors. Consequently, the understanding of the challenges of transformation is already relatively elaborate. Still, many uncertainties and knowledge gaps persist.

Germany in general, and the Rhine-Ruhr region in particular, have seen significant efforts in modelling and estimating the effects of different transformation pathways toward a climate-neutral industry. At the national level, several studies have modelled potential scenarios and pathways for decarbonisation in the industrial sector, employing bottom-up technological models that are also part of TRANSIENCE's model armoury, such as FORECAST and WISEE-EDM (Agora Energiewende und Wuppertal Institut, 2019; Herbst, 2022; Prognos et al., 2020, 2021). All these studies show that decarbonisation is technologically feasible by 2050 or even 2045. However, these studies lack regional granularity, failing to depict the specific effects on individual German regions. Furthermore, while circular economy measures, such as recycling and material efficiency have been included in some of the studies mentioned above, research focusing solely on circular economy hasn't yet utilised industry transformation models (IN4climate.NRW, 2021; Wilts, 2022). At the regional level, only one study describes petrochemical clusters using the WISEE-EDM model (Scholz et al., 2024). In this study, the Rhine-Ruhr petrochemical clusters are described in detail, but no scenarios for decarbonisation are modelled. Apart from that, mostly political strategies, such as a hydrogen roadmap and a carbon management strategy are formulated for the regional level from political stakeholders.

One of the key concerns of participants emerges from Germany's positioning as an economy. Participants shared concerns on how a changing global trade regime may affect German industry competitiveness. Currently, Germany still holds a significant industrial production of the first and most energy-intensive steps of basic raw material production in the industrial value chain. On the one hand, participants see this as a key advantage highlighting the strong cross-sectoral integration in synergistic clusters as a key competitiveness advantage. At the same time, they realise that regional energy prices in general and prices for green hydrogen in particular will hardly ever be competitive with other regions with more favourable conditions for large scale renewable energy supply. An alternative strategy might be to import intermediate products, thereby outsourcing the energy- but not very labour-intensive part of the value chain to improve the competitiveness of later high-value added steps of the production chain. However, the key uncertainty is how much of the competitiveness advantage resulting from the clustering and cross-sectoral integration might get lost if individual steps of the value chain are relocated. In other words: which of the locational (dis)advantages dominates: higher energy prices or local network effects and synergies from cross-sectoral integration? A better understanding of what role secondary raw materials may play in mitigating some of the geopolitical effects outlined above may also provide helpful insights for more informed transformation strategies.

A second major concern relates to a major investment backlog both in industry and the public sector. Many industrial assets are approaching the end of their technical lifetime requiring urgent reinvestment. But the many uncertainties related to the demand for green products and availability of low (enough) cost green energy and feedstocks makes these investments in many cases "unbankable" as it is hard to convince a bank to provide a major loan for a product that does not have a market (yet). The investment backlog is also highly visible in the public sector. Germany's infrastructure is aging and requires massive public investments, especially railways, bridges but also digital public administration. However, after last year's federal constitutional court decision to uphold states' debt ceilings, participants are doubtful whether the German government still has the fiscal power to stem those investments. Consequently, they are concerned that the government will have to face tough decisions regarding how to spend scarce resources which might undermine fiscal support for the industrial transformation or thwart political stability overall if industrial transformation is prioritised over broader social policy issues. Here the key issue is to better understand the potential trade-offs that political and economic decision makers will have to face in a situation of limited fiscal investment capacity.

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4 CE strategy in EU policy context for three focal sectors: Concrete, Steel and Plastics

CE policy development has been significant in the last decade. The first Circular Economy Package[2] of measures was launched in 2015. The Circular Economy Action Plan (CEAP)[3], released in 2020, contained 35 measures which have all been completed by now. The CEAP focused on the development of product regulations that encouraged the introduction of CE principles in their design, a revised monitoring framework and action around ambitious waste recovery targets.

While the CEAP is part of the EU Green Deal, there is still lack of adequate integration between decarbonisation and CE interventions. While CE strategies could contribute to the net zero pathways of energy and material intensive sectors such as steel, cement and plastics, there is little understanding of their true decarbonisation potential, with most sectoral roadmaps and vision documents tending to view the two transitions independently rather than jointly.

In the sections below, we discuss some of the key policy developments in each area and emphasise policy developments as well as gaps in advancing decarbonisation and circularity.

4.1 Steel: decarbonisation and the circular economy

Steel is a core component of modern societies and key in the development of other industries including buildings, infrastructures, transport, energy or machinery. Globally, steel manufacturing represents around 7% of total GHG emissions, and around 5% of GHG emissions in Europe (IEA, 2020). The net zero transition is also highly reliant in steel. Existing wind turbine models require between 107 and 132 tonnes of steel per MW of installed capacity and PV panels around 60.7 t/MW, which makes steel one of the foundation materials for decarbonisation (Carrara et al., 2020). In fact, according to IEA, steel is among the last sectors using coal as reduction agent by 2050 (IEA, 2023). However, the decarbonisation effort will require a mix of different technologies. In the IEA NZE scenario, the reduction of emissions will be achieved through a combination of technology options. By 2030 the share of production by blast furnace (BF) decreases by around 10 points and is compensated by 5 points increase in the Electric Arc Furnace (EAF) route using scrap (IEA, 2024). While scrap recycling is currently at around 85%, there are limitations in scrap availability given future demand developments.

The other two key technology routes are hydrogen paired with Direct Reduction Iron (H2-DRI) and CCUS which in the IEA NZE scenario may represent around 8% of primary production by 2030 (ibid). However, most of the steel decarbonisation pathways place little emphasis on demand management through CE strategies.

The Fit for 55 initiative aims to achieve a reduction of domestic greenhouse gas emissions by at least 55% by 2030 compared to 1990's level. This involves changes in the carbon pricing and free allocation of permits, including the introduction of a Carbon Border Adjustment Mechanism (CBAM), a new instrument that applies tariffs on imports of emission intensive goods such as steel products that are at risk of carbon

[2] EC COM/2015/0614
[3] EC COM/2020/98

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leakage and which will become effective in January 2026.

While most of the focus has been on steel decarbonisation, the sector is inherently suited for circular economy initiatives, giving on the high durability of steel and efficient recycling. However, CE policies in steel manufacturing are still underdeveloped. There have been attempts in the construction sector for increasing reuse of structural beam elements, but this is still faced with multiple obstacles including storage, testing, insurance and certification. Most building standards place little emphasis on CE opportunities. Building passports are among the tools that could contribute to better identification of steel in the building stock and promote reuse and recycling loops, but their application is still in early development.

The sector has also historically engaged with exchanges of heat and by-products. Steel slag is a valuable by-product with multiple applications, especially in the production of cement, and waste in steel manufacturing can be recovered back into the production process. The sector has also been active in industrial heat networks and heat exchanges which can contribute to energy reduction. Recently, there has also been initiatives to use circular carbon, recovered from biowaste, as an alternative to conventional fossil fuels.

Steel in cars is currently addressed through the End-of-Life Vehicles (ELV) Directive[4] which sets targets for steel part reuse and recycling. Some industries such as automotive, equipment and aerospace have also advanced considerably in remanufacturing of components, but in some of these cases existing safety regulations may pose obstacles to further develop circular strategies.

In the UK, the Centre for Circular Metals proposed a roadmap for circular steel production, outlining a pathway to reduce CO_2 emissions by over 90% by 2050. This roadmap prioritises increased steel recycling via EAFs, reducing reliance on blast furnace methods, and integrating reuse and remanufacturing strategies to extend the lifespan of steel products. It also highlights the importance of aligning these technical solutions with policy and regulatory frameworks to achieve the desired emissions reductions (CE Hub, 2024).

4.2 Cement: decarbonisation and the circular economy

Similar to steel, cement is also a central sector in the policies for decarbonisation. Currently the production of cement contributes to around 8% of total global GHG emissions and around 4% of the GHG emissions in the EU. Cement is also among the material foundations for the net zero transition required for main renewable energy technologies and required infrastructures (Carrara et al., 2020). The sector is subjected to the EU Emissions Trading System (ETS) and soon also to the CBAM.

In 2020, CEMBUREAU published the Net Zero Roadmap to decarbonise cement production. While the roadmap focuses on technologies for decarbonisation it also points to the complementary role of circularity to reduce emissions along the value chain. This roadmap emphasises the use of alternative raw materials and fuels by valorising difficult-to-recycle waste streams. According to CEMBUREAU, by 2050 the use of waste materials, co-processing, both as raw material, or as a source of energy, could replace as much as 60% of traditional fuels and a large fraction of raw materials. Around 50% of the alternative fuels could be bio-based representing important potential for GHG reduction (CEMBUREAU, 2020). The cement sector is already actively seeking these opportunities, and some countries achieve over 80-90% fuel substitution.

It has been estimated that by 2050, 40% of kiln energy will come from traditional sources, i.e. coal (30%) and

[4] Directive 2000/53/EC

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petcoke (10%), while 60% of kiln energy could potentially be provided by alternative fuels of which 40% could be biomass. This fuel mix would lead to an overall decrease of 27% in fuel CO_2 emissions. The focus on decreasing embodied carbon of cements, especially in construction, has already had an effect in changing the preference for cement types with lower clinker content. For example, the Portland cement, has lost market share in favour of Portland Composite (CEM II) and Blast Furnace Slag Cement (CEM III), both of which highly rely on alternative raw materials and use of by-products of other industries (e.g. Blast Furnace Slag cement) as well as limestone replacements (Xavier & Oliveira, 2021). Most of these shifts have been mainly motivated by reductions of costs and embodied carbon emissions rather than policies. Strategies such as reducing cement content in concrete mix, using secondary aggregates for concrete, or avoiding over-specification of concrete have all been mostly guided by GHG reductions but have also led to important material savings.

Changes in waste and ambition targets of landfill diversion for construction and demolition (C&D) waste have also promoted CE strategies. Concrete makes a large fraction of demolition waste. Current practice recovers part of the concrete for lower quality applications such as secondary aggregates and reprocessed concrete for roadworks. If demolition is adequately planned, through instruments such as demolition audits and demolition waste plans, concrete could be recovered for higher value applications.

4.3 Plastics: decarbonisation and the circular economy

As per cement and steel, plastic is also a foundational material of modern societies. Initially a by-product of the oil industry, its versatility and low production cost has led to an exponential growth in the use of plastics since their introduction in the 1950s. Geyer et al. (2017) estimated that all plastics ever made amounted to about 8,300 Mt, of which about 6,300 Mt have become waste. Moreover, only around 9% of all waste has been recycled globally, while around 80% has accumulated in landfills or directly in the environment (ibid).

Increasing citizen awareness around the problem of plastic waste and changes in the trade of plastic waste after the introduction of the China's Operation National Sword policy[5] triggered further policy focus on plastic waste. The packaging directive and its recent review into the Packaging and Packaging Waste Directive[6], have established stringent targets on plastic packaging waste prevention and high-quality recycling. This includes a reduction in packaging waste of 5% by 2030 and 15% by 2040, better information about material composition of the packaging and targets on reuse of packaging. Also, by 2030 all packaging put on the market must be recyclable. Packaging is also part of Extended Producer Responsibility schemes to financially contribute to its management and an economic instrument, the plastic tax/levy, charging non-recycled plastic packaging waste produced by member states which have resulted in unharmonised application of plastic levies across member states. New regulations around single use plastics also ban single use plastics in some applications and introduce new obligations. However, less has been done for other types of plastics which are ubiquitous and used across all industrial sectors and represent around 60% of all plastics. The revised ELV Directive proposes a minimum of 25% recycled plastic content in new vehicles and a 30% recycling target of plastic parts in vehicles and some incentives to encourage the sale of spare parts.

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[5] A policy initiative that, among others, banned the import of contaminated plastic wastes to China.
[6] Directive 94/62/EC, last amended in 2018/852

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Plastics in construction are poorly regulated. New composite materials in construction, aerospace and other industries have also created new materials which are strong and lightweight but may be difficult to recycle at the end of life.

Thus, CE strategies in the sector mainly focused on packaging and overlooked other more complex plastic products. Despite the introduction of new reuse and prevention targets, most of the emphasis is on promoting less preferable options from a CE perspective, mainly focusing on plastic recycling. Even for plastic packaging, the recycling rate is to achieve 50% by 2030 and 55% by 2040, which is comparatively less ambitious than for other packaging materials, recognising the inherent added difficulty of recycling a wide range of plastic polymer materials.

4.4 Lessons for the design of MIC3

The review of the policies shows that while advances have been made, especially in the area of product regulations to embed selected CE principles in the design of products, there is still limited and fragmented interventions towards the CE as a whole. The sectors analysed highlight that still many of the initiatives focus on more conventional recycling options, while adopting more ambitious CE strategies such as reuse, or life extension do not always fit into the system practice. For example, most interventions in construction have been directed towards recovery of C&D waste. Progress in the reuse of building materials and components has been comparably slow, given a poor understanding of material degradation over time and the requirements for costly retesting and re-specification, which are not adequately recognised in building regulations and certification schemes.

Similar to the slow progress on development for CE policies, modelling of CE options using conventional modelling approaches tend to focus on recycling and secondary material production, but existing modelling approaches encounter limitations when trying to reflect policies around the slow and narrow loops and ability to reflect value creation associated with new business models.

By adopting an integrated approach **MIC3 should** aim to better reflect complex set of system wide implications of ambitious CE strategies across the economy. This requires understanding of the linkages between physical material flows and its monetary counterpart and connect it to energy models to reflect changes in carbon intensity of, for example, reuse and closed loop cycles, and impact on overall economic and social indicators such as GDP and jobs. To be able to do that, the model requires a complex understanding of interactions across the system reflected in better specified input-output tables, data on production change costs associated to CE interventions (e.g. reduction in material costs) and interactions across systems (e.g. textiles and plastics or automotive and plastics and textiles).

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5 Data exchange and open-model interfaces

Technically, the MIC3 model framework will integrate various satellite modules focused on socio-economic, techno-economic, material flow, life cycle assessment and energy system planning. The following modules will be connected within the MIC3 framework:

1. **OpenPROM**: Energy system simulation model
2. **OpenGEM**: Macro-economic CGE model
3. **FORECAST-Industry** and **EDM-Invest**: Techno-economic industry models
4. **EU-MFA**: Integrated European material flow analysis
5. **SIMSON**: Global material flow model
6. **PREMISE**: Life cycle assessment module

The number of different modules involved, and the variety of model foci highlights the need for flexible and well-defined interfaces for data exchange. Using the formatting of IAMC data templates and adapting them to the specific model needs will provide a basis for structured and integrated open-model interfaces and connections. Inputs and outputs for each module have been identified and collected based on a 'baseline' workflow (Figure 3).

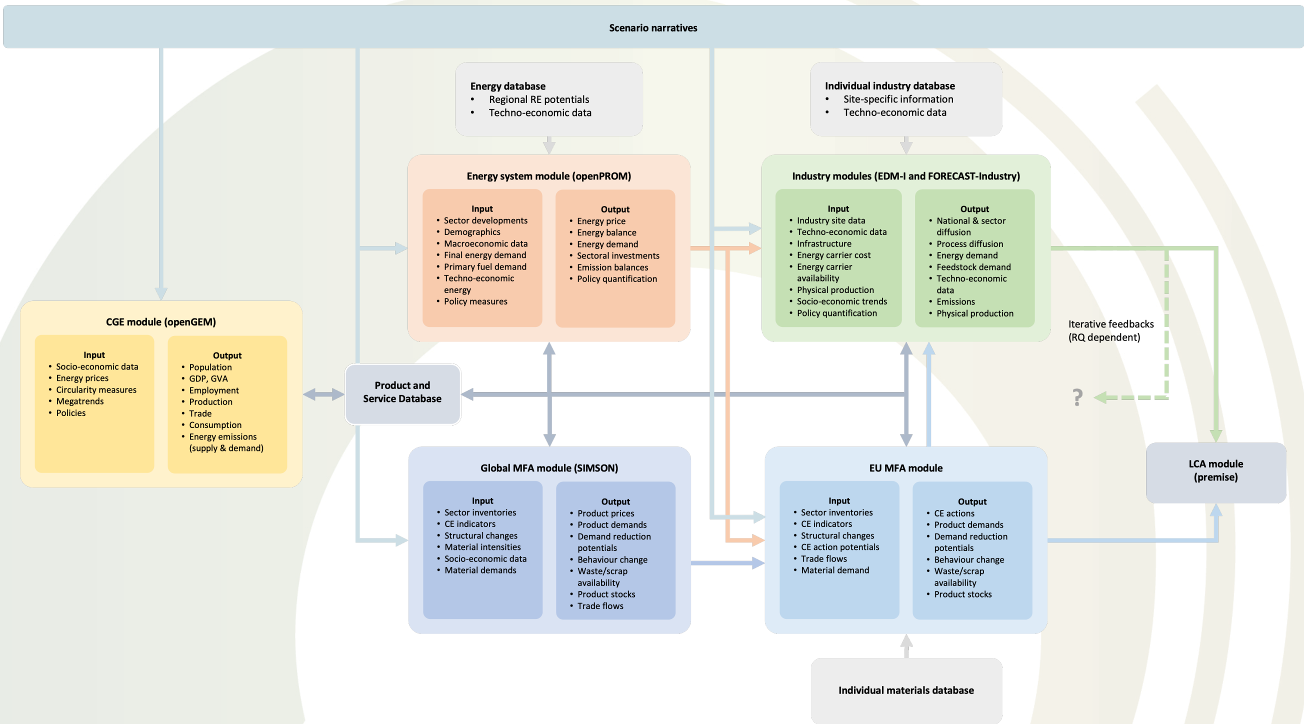

Figure 3. Baseline module coupling and interfaces for data flows within the MIC3-framework

The baseline workflow addresses industry-related research questions driven by energy system developments and circular economy measures. OpenGEM initiates the model chain by translating scenario narratives into socio-economic developments (e.g. GDP growth, industrial production in monetary terms). OpenPROM then investigates the energy system, interacting with the global MFA for indicators like product prices and trade flows, and provides price projections to the technoeconomic industry model FORECAST (i.e. electricity price, CO2 price) and sectoral developments to the EU-MFA module (e.g. about the new car

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registrations). The EU-MFA calculates demand reduction potentials and product demands in line with circular economy measures. Industry modules analyse process diffusion in industrial plants to quantify emission reduction, energy and feedstock demand, and techno-economic indicators. Feedback loops between models, especially between industry modules and OpenPROM and OpenGEM, may be necessary, to quantify the broad socioeconomic impacts of industrial decarbonisation pathways. Results from all modules will be fed into PREMISE for an LCA of the developed scenarios.

The workflow schemes and interfaces are dynamic documents, evolving with the project. Detailed connections for each module will be defined and established. Alternative workflows have been drafted for different kinds of research questions, such as energy system-related questions driven by circular economy measures, macroeconomic questions driven by industry sector developments, and material flow-related questions from industry sector developments. These workflows will be extended during the project ensuring a flexible open model framework.

Data exchange is crucial for the MIC3 framework's development and establishing a consistent and robust methodology ensures proper integration of its modules. Key data exchange considerations and factors include format (e.g., JSON, XML), volume, frequency, latency, security, and compliance with regulations like the General Data Protection Regulation (GDPR). In the first phase, WP4 identifies the data format and preliminary interfaces between modules. The project aims to adopt the IAMC time series data template, widely used for model intercomparison, which enhances transparency and data consistency across models and will enable data exchange at the interfaces of the framework. The IAMC template uses a hierarchical system for naming variables, improving consistency and clarity across datasets. The set of variables of the IAMC template will be enhanced to cover all aspects relevant to TRANSIENCE and to cover all interfaces, including possible iterations between modules, parameters of scenario narratives and output reports. The specification of variables will leave no room for ambiguity, and this will be ensured by clear definitions, and sectoral and regional mappings, and will be checked with appropriate data validation processes and comprehensive vetting.

Data validation is essential for ensuring the accuracy and integrity of information exchanged within the MIC3 framework. The validation process will be divided into two key types:

1. Syntax validation: Ensures that the data is formatted correctly according to the IAMC template.
2. Semantic validation: Ensures that the data is contextually correct, logically consistent, and aligns with historical data and scenarios.

The validation process will extend across all satellite modules, verifying logical relationships and consistency between sectors and regions and is envisioned to be implemented with scripts that would automatically check the structure/syntax of the data exchanged. Ongoing work in these areas will be documented in future project deliverables.

6 Open model development strategy

The current open model development strategy focuses on the first phase of TRANSIENCE (M1-M18). This strategy is strongly motivated based on the inputs from the CE policy spectrum, the stakeholder views obtained so far, and the model development to this day. The following steps are proposed based on the current knowledge and information gathered. The model development should not be treated as a fixed planning but rather a dynamic and iterative process.

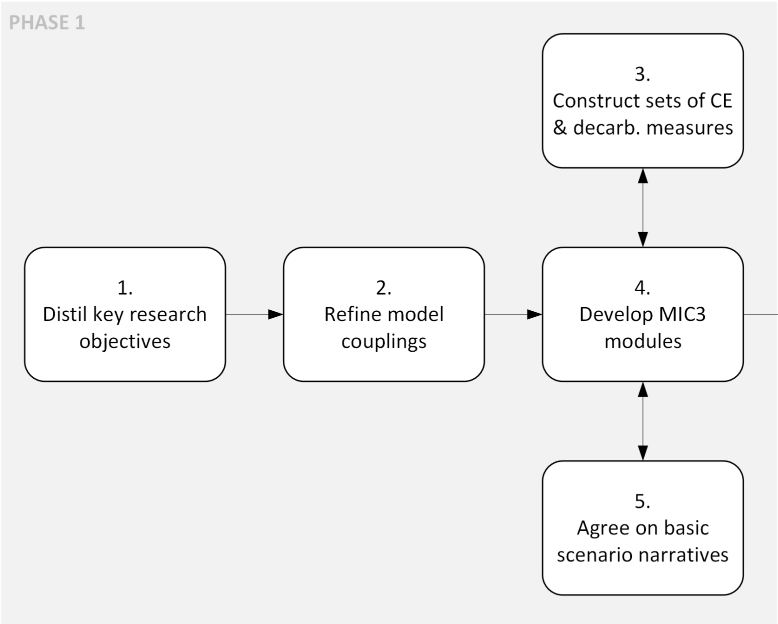

Figure 4. Diagrammatic representation of the open model development strategy

1. Distil key research objectives from stakeholder and policy insights

The diverse modules within the MIC3 modelling framework offer a great potential of capabilities, but it is essential to make strategic choices about what can and should be modelled. Throughout the ongoing stakeholder engagement process and the CE policy mapping, it has become apparent that stakeholders and current policies often have specific concerns they want addressed. As a starting point for this strategy, we recommend translating the insights gained from both stakeholders and policy reviews into clear research objectives. These objectives will guide model and scenario development decisions.

2. Refine model couplings and interfaces

Important milestones have been achieved with regards to model development. Preliminary module interfaces have been identified (MS5) and data exchange and validation protocols established (MS8). In the upcoming period, the preliminary plans should be re-evaluated and further elaborated in order to verify that the envisioned workflows and interfaces conceptually fit the purposes of the research objectives identified in Step 1 and, where needed, detailed data flows should be augmented. Note that this is an iterative process and will span at least throughout the first phase of the project, culminating in beta modules at the end of the first phase. Intermediate work, such as for D3.4 'Framework for industry transition modelling', will also be utilised to accommodate this process.

3. Construct a systematic set of CE and decarbonisation measures actionable for models

The integration of circular economy and decarbonisation options is a cornerstone of the MIC3 framework. A comprehensive set of policies and technologies will be developed (MS10), with their costs and potentials parameterised for model integration (MS11), and ultimately published as an open-access database on the I^2AM PARIS platform (D3.5). Further insights into the impacts of circular industrial transition pathways and their implications for model development will be gained through ongoing work. D3.6 will explore how CE measures contribute to mitigation efforts, D3.7 will assess the effects of circular transitions on European competitiveness, and D3.9 will analyse actor interactions within specific industries to better inform modelling assumptions.

4. Develop the MIC3 modules

Guided by and incorporating the learnings of the activities outlined above, the tasks of WP4 will be dedicated to the advancement of the constituting modules of MIC3 (D4.1-D4.7). The development of the modules will be carried out under open science protocols, including open-source licensing, to ensure transparency, accessibility and reproducibility (D3.9). The success of this stage of model construction requires effective collaboration between the involved project partners, which has been present throughout the project since the beginning and is expected to intensify for the rest of the development phase. The achievements of this development will deliver satellite modules suitable for the progression and testing of the larger, connected MIC3 modelling framework.

5. Agree on basic scenario narratives

Firstly, the narratives of the baseline scenario(s) based on the current circular economy policies and decarbonisation strategies should be clearly defined (inputs from steps 1-3), including the boundaries and scopes that will guide the use of MIC3. Secondly, narratives for alternative scenarios should be agreed based on needs from the industrial stakeholders, as the potential users of MIC3 in the future, the development of CE policies in the three focus sectors, and the scenarios narratives from the existing decarbonisation models. The construction of scenario narratives should explore the feasibility of aligning with sister project AMIGDALA and similar projects such as CIRCOMOD, to increase the synergy and promote collaboration.

In the second phase of TRANSIENCE, the individual modules should be **integrated** into the MIC3 framework, followed by comprehensive **validation,** and the (preliminary) results should then be **interpreted**. The feedback from validation and interpretation should then be used to further improve MIC3. Last but not the least, **user interfaces** for potential users, such as industrial stakeholders, should be constructed. This model development strategy document does not deviate from the planning from the second phase of the TRANSIENCE project.

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