

TNO report**TNO 2021 R12237****Learning from circular economy relevant
modelling approaches**

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S. Raihan (2004)

Iqbal, Z., & Siddiqui (2001)

D. Van Vuuren (2015)

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Executive summary

It is important to understand the economic, social, and environmental impacts of circular economy policies, as such policies are expected to become widely applied in the coming years. This project investigates which (combinations) of models and approaches can lead to a modelling suite that is capable of doing such analyses.

Research objective

Current dynamic social-environmental-economic models have been usually developed and successfully applied for the evaluation of climate and energy policies. Examples are Integrated Assessment models (IAMs) like IMAGE, and (partial) Computable General Equilibrium (CGE) models such as GTAP and EXIOMOD (usually using static Input-Output tables as a basis). The Netherlands Environmental Agency (PBL) is interested to see how such existing models could be further developed, so that they become suitable to assess the impacts of circular economy (CE) policies at EU and National levels. The existing dynamic models are however not well suited for this. First, they usually have a low product and sector resolution – sufficient when e.g. analysing the introduction of a limited number of new energy technologies, but insufficient for analysing CE improvements, which are highly product specific. Second, they often are based on monetary instead of physical data which do not provide a good representation of the waste sector and circular strategies such as refurbishing, repair and component reuse. Third, CE options require insights in product stocks in use in society that become obsolete and then available for re-use, refurbishing or recycling, and most existing dynamic models focus on flows, not stocks. On the other hand, there are bottom-up methodologies such as Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) that have a high level of detail and capture stock dynamics, but the lack economic feedback loops such as price elasticities, substitution elasticities, and so on, that dynamic economic models cover well.

The key research question of this study will be to evaluate how to characterise and combine a range of top-down dynamic and bottom-up static quantitative modelling approaches, that could be integrated into an improved modelling toolkit.

Exploring new combinations of modelling approaches

This study used a few existing modelling approaches and models as a basis (i.e. IAM's, CGE's, Partial equilibrium models, LCA, IO analysis, Hybrid LCA (which combines LCA with IOA) and MFA). This report uses CE case-studies to think through theoretically the strengths and weaknesses of individual modelling approaches and the additional strengths obtained from combining two or more modelling approaches. The following case-studies were used to discuss the options and requirements of the modelling approaches:

1. Target of priority/agenda/sector manufacturing to avoid net outflow of critical raw materials by 2030.
2. Introduction of lease services (servitization model), creating new links between several manufacturing sectors and service sectors. What will be the impacts of shifts from manufacturing to service providing in the final consumption of certain goods?
3. Target of priority/agenda/sector construction, to reduce primary raw material input in 2030 by 25%. How can such a target be met?

4. Target of priority/agenda/sector plastics to reduce plastic waste incineration.
5. How can a better standard for MPG ("Milieu-Prestatie-Gebouwen") stimulate use of wood in construction?
6. Recycling, what if X% of plastics are either mechanically or chemically recycled.

In principle, over 30 combinations of models would be possible to analyse such cases, but we focused on a few combinations earlier reported in literature (i.e. IOA and LCA, IOA and MFA, CGE and MFA, CGE and LCA, IAM and LCA and LCA and MFA).

Discussion

The key in modelling CE policies is that models or combinations of models should be able to combine the following elements: accommodating high level of detail available in bottom up LCA/MFA models, insights in product stocks and vintages and the outflow of obsolete products that can be subject to CE improvements as provided by dynamic MFA models, and the dynamic aspects related to for instance price elasticities and product/technology substitution elasticities as present in dynamic models. IAMs such as IMAGE and CGEs such as EXIOMOD should deliver insight in the dynamic aspects of circular changes. Partial equilibrium models by nature do not cover the full economy.

If we want to include detailed LCA or MFA like stock-flow information in an economy wide approach, e.g. IOA or CGE, the mathematical methodologies in general are well established. Most of such detailed LCA or MFA information is however not structurally available or if it is, such as the micro-data of CBS, not available publicly. This gap might be filled step by step for the Netherlands, starting with sectors relevant for specific circular economy questions or using generic databases (such as the life cycle inventory database Ecoinvent) as a stopgap. Another problem is that a full integration of high product detail in dynamic models (IAMs or CGEs) will make the overall model too heavy to make good model runs in a reasonable time span. In practice, currently even in studies with detailed CGEs with 160 sectors and 48 countries like EXIOMOD usually sectors and countries outside the study focus are aggregated to ensure a reasonable model run time.

The most promising route seems hence to use a (dynamic) MFA approach to analyse product stocks and particularly end of life flows. LCA then can be used to analyse in detail the improvement options, scaled up to national volumes of product use. Such information can be soft-linked to a dynamic model, to get insight in how changes work out dynamically in the wider economy (e.g. by aggregating detailed information on a few products to a specific product category in a CGE, or to add a specific product category in the input-output database underlying a CGE). This approach was recently also proposed by a consortium that submitted a major proposal on (among others) CE modelling to the Dutch National Science Agenda aiming to support the work on CE monitoring.

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1 Introduction

It is important to understand the economic, social, and environmental impacts of circular economy policies, as such policies are expected to become widely applied in the coming years. This project investigates which (combinations) of models and approaches can lead to a modelling suite that is capable of doing such analyses.

1.1 Defining the scope of the study

There are many models to consider when assessing economic, social and environmental impacts. Firstly, we will have a look at the top-down approaches featuring macroeconomic models. Several quantitative modelling approaches to conduct impact assessments for sustainability policies are well established and based on scientific publications in recent decades. These approaches continue to look for further development options to model some of the complex relations of a circular economy. On a macroeconomic level, an important class of impact assessment models are based on general equilibrium models. These models can comprise of many relevant economic, social, and environmental aspects. However, a general equilibrium model, or any modelling approach for that matter, is only meaningful if it maps out the most important mechanisms in one empirically justified manner. Only then can it provide a relevant quantitative picture of the consequences of exogenous developments and policies for the economy and for the use of raw materials and associated resources related environmental pressures.

Current dynamic social-environmental-economic models have been usually developed and successfully applied for the evaluation of climate and energy policies. Examples are Integrated Assessment Models (IAMs) like IMAGE, and (partial) Computable General Equilibrium (CGE) models such as GTAP and EXIOMOD (usually using static Input-Output tables as a basis). The Netherlands Environmental Agency (PBL) looks to develop existing models into a new tool, that allows to capture essential mechanisms for a national and European circular economy policy evaluation tool.

Current CGE models are often based on an input-output table (IOT), which is linked to various economic feedback mechanisms. Examples are investment amounts in relation to savings, increases in productivity in relation to investments in sectors, price changes in relation to changes in product demand, wages / benefits to employees and final consumer demand, and ratio of domestic production versus imports of products. Circular economy strategies such as life extension and more material efficient production have been calculated, in a more or less satisfactory manner, with such models. It is then assumed that a longer lifespan of a product group results in a lower final demand, or in the case of material efficiency that a product group can be made with fewer intermediate inputs.

An important limitation in the macro-approaches is the granularity of the underlying IOT databases. Often such databases have only 60 (GINFORS) to 163 (EXIOMOD) economic sectors. For example, sectors relevant for circular economy analyses, the waste sector and material recycling sector, are often not represented, or are represented limited.

These sectors, which comprise of a wide range of processing and recycling techniques, are for example, represented as 1 sector in the database. In addition, the monetary flows from IO tables, given the different costs of waste processing, have limitations as estimators for the physical flows (of goods). Another limitation of the macro-approaches is that important CE strategies based on repair, refurbishment and component reuse are hardly visible in the IO tables given the common descriptions of economic activities.

In summary, the existing dynamic models cannot give a representation of the measure to circular economic strategies that is needed for policy analysis.

We can also consider the bottom-up approach of LCA (Life Cycle Assessment). The great advantage of using LCA methods for calculating CE strategies is the high level of detail. These methods follow the physical product and material flows and can thus be used to determine the impacts of CE strategies on a product (group) such as life extension, repair, refurbishing, component reuse, more efficient production, and recycling. However, the disadvantage of the LCA method is that it only describes marginal changes in a fixed world - such as what is the impact if you serve coffee in a cup instead of a plastic cup in one location. The static nature of the LCA method could make it unsuitable for analyses involving large-scale changes in the economy as expected because of for instance the energy or circular transitions.

LCA can include changes in the specific product system being investigated. For instance, changes because of improvements in efficiency (in terms of costs and environmental impact) of new CE techniques or designs. These technological improvements, production techniques that still go through learning curves, can be captured in the LCA-method. Inclusion of these technological developments in the LCA are also known under the heading of 'ex ante LCA' and are part of new methodological developments in the field of the LCA.

1.2 Towards a research objective

Both CGEM and LCA modelling approaches have a set of analytical limitations. Ranging from the level of detail, the account of the evolution of stocks in the economy or the ability to do large scale impact assessment. It would therefore be worthwhile to look at several types of modelling approaches, each of which can be used to map a specific aspect of the development of the circular economy. Each model has its strengths and weaknesses and none of them is comprehensive to such an extent it meets all requirements to evaluate a policy relevant research question.

The key research question of this study will be to evaluate how relevant CE policy issues can modelled and policy questions answered using this range of quantitative modelling approaches, or combinations of such approaches (see examples in Textbox).

Textbox: background of the core objective of study

In current practice, experiments are being conducted with different combinations of the macroeconomic modelling approaches and mostly microeconomic LCA (Life Cycle Assessment), depending on the question to be answered.

Initial questions on the macroeconomic level are for instance: what are the (direct and indirect) impacts on the economic system and environment when the market penetration rate of a CE measure increases significantly? For example, what is the influence of a large penetration of the electric car on primary material use, electricity production, and crude oil based products. What are the additional dynamic and structural economic effects of e.g. **effects that occur in the background of an LCA analysis**? An example of expected developments in the background of an LCA analysis is the energy mix used in the future. It is expected to have a much lower CO₂ emission than currently, which increases the environmental benefits of CE strategies on the long run. These structural economic developments can be modelled explicitly. Following the initial macro questions, people look for answers typically answered by an LCA. A frequently used approach is to combine an LCA / IO-LCA with CGE or IAM models, whereby the IAM or CGE provides a picture of the future structure of the economy within which an assessment at a more specific level of detail can be done with LCA.

The above model combinations are the first steps towards a better assessment of effects of and the progression of penetration of CE strategies such as following the lifespan extension, repair, refurbishing, component reuse, more efficient production and recycling at specific product level. Obviously, more complex and comprehensive questions can only be answered with such model combinations combining the strengths of the LCAs, ex-ante LCAs, CGEs, IAMs and MFAs within one framework.

Firstly, it must be investigated which policy questions can be answered with a single model. The next question is which question can be answered with one or more model combinations. How a model combination precisely combines the advantages of LCA (detail and physical representation of reality) with the advantages of models such as CGEs and IAMs (taking into account dynamic and structural effects on the economy) when calculating the economic and environmental implications of CE strategies is the next question. And, as the models cannot predict a future, it is important for this model framework *how* future scenarios can be used in these model combination (s).

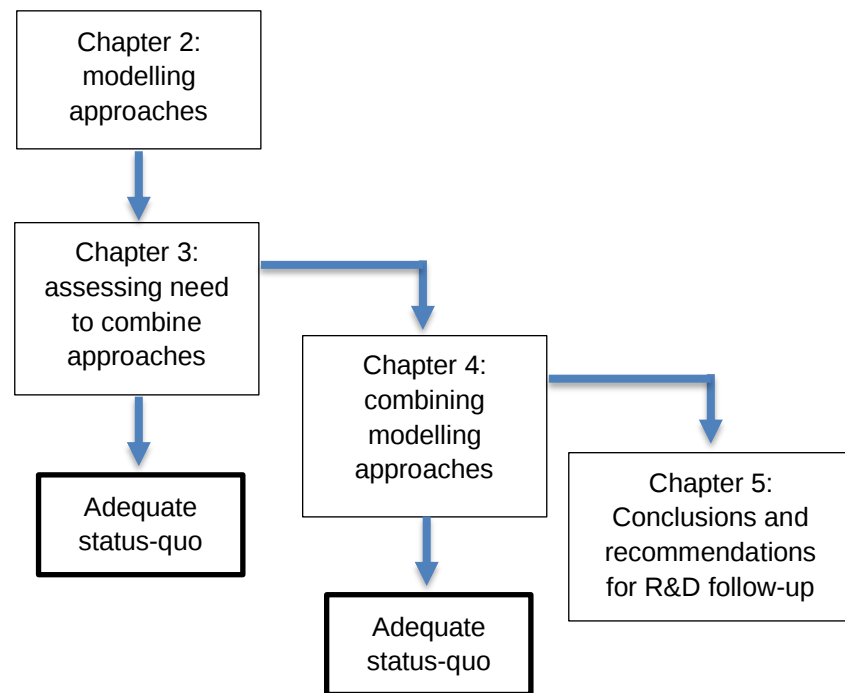
We expect that through a combined analysis, the upscaling of the CE measure, both their penetration as their effects can be modelled better. The core objective of this study is to characterise individual approaches and create recommendations to develop individual approaches to an improved modelling toolkit for CE purposes.

Naturally, the latest developments of new, more detailed SUT / IO databases must also be included, as developed for instance in the FINEPRINT and PANORAMA projects. The OECD has a program that is worth of the attention of anyone developing macroeconomic assessment tools. Another point of attention is the relationship between a CGE-LCA combination with the scenario work that PBL and CML are currently undertaking for the UN International Resources Panel, and that combines the IAM IMAGE with LCA.

It is important to note that in this study, circular economy strategies are often referred to as policy options. It is however not straightforward how circular strategies fit a certain policy option. In turn, a policy action objective (achievement) is not like the definitive policy goal (effect). The difference between circular strategies, policy options and policy goals will be only implicitly part of this study.

Figure 1 shows (the implication of) the sequence of the chapters in this report.

Figure 1: sequence of chapters and their implications



1.3 Out of scope

We will round-up the introduction by briefly discussing some modelling approaches that are not in scope of this report. In general, it can be said that modelling approaches featuring insights from behavioural economics are not represented in this work.

A class of econometric models, such as E3ME, represents an approach that turns away from CGE computation and uses several econometric relations as a basis of the model. Therefore, real world phenomena such as imperfect knowledge or path-dependency are said to be better represented than in IOT based models.

One could also opt for an Agent-Based-Modelling (ABM) approach. This approach uses quantitative models that simulate decisions of autonomous agents that interact with decisions of other agents. Examples of these interactions are effects on price, quantity, quality, risk-behaviour etc. Agents can be both an individual human being as well as an organised entity such as a company or a public office. It is possible to combine ABM approaches with some of the models discussed in Chapter 2, see for example (Belete et al. 2019).

If particular and significant types of decisions, such as adjusting procurement behaviour of a company in face of a tax regime change, need to be analysed, a Discrete Event Simulation (DES) might be the preferable approach. DES focuses on how various deterministic and stochastic events trigger the dynamics of the

entire system rather than continuous and predictable feedback loops such as annual production and consumption patterns.

Operations research (OR) is used to describe an approach based on a suite of tools such as multicriterial decision-making (MCDM) tools, game theory applications and other optimization algorithms. Furthermore, experimentations aimed at empirical evidence (in a workshop or another confined time-space) can be regarded as a modelling approach as well. Lastly, system dynamics (SD) is a relevant simulation approach that models complex systems by mapping out their feedback mechanisms. It describes systems with stocks, flows, and additional parameters, which makes it particularly relevant for an advanced type of Material Flow Analysis.

For a convenient introduction of modelling approaches both inside and outside the current scope, we refer to (Walzberg et al. 2021; McCarthy et al. 2018).

2 Descriptions of relevant modelling approaches

In this chapter the characteristics of the following modelling approaches will be discussed.

Static stand-alone modelling approach

- Environmental LCA
- Input-Output analysis (IOA), including physical (p)IOA

Dynamic stand-alone modelling approach

- Material Flow Accounting (stocks and flows)
- Computable General Equilibrium Modelling
- Partial Equilibrium Modelling
- Integrated Assessment Modelling

Established combination of two modelling approaches

- Hybrid LCA

Every method or approach is discussed by a short description, the general purpose of the modelling approach, the data requirements of the approach and the most important advantages and disadvantages.

2.1 Environmental life cycle analysis (LCA)

2.1.1 *Short description of modelling approach*

LCA is a widely accepted tool to systematically quantify environmental impacts along a product's (or service's) life cycle (from resources extraction to waste treatment). The basic idea is to compare the environmental performance of different products or technologies for providing a certain function. By considering a broad range of environmental impacts and all (most) life cycle stages, the trade-off between impacts and life cycle stages are to be identified. LCA is generally and according to (ISO) performed in 4 steps:

1. Goal and scope definition
2. Life cycle inventory
3. Life cycle impact assessment
4. Interpretation

LCAs can be categorized in several ways, many of them relating to how the inventory data are compiled: consequential vs. attributional, process based vs. IO based, hybrid (of the former two). Data gathering in environmental foot printing is can be classified in process-based life cycle assessment (Process Based Analysis (PBA)) and Environmentally Extended Input-Output modelling (EEIO or Input Output Analysis (IOA)). Recently, more and more prospective, or ex-ante LCAs are conducted that try to assess impacts of technologies/products at a future point in time. Likewise, there are many methods available for the impact assessment step, but these are out of scope of the current overview.

The process-based LCA traditionally focused on assessment and comparison of impacts of the production of specific (industrial) products with detailed modelling of production processes and on identification of impact hotspots along the product chain.

A major drawback of this approach is the immense need of data when including upstream processes and their interactions and the need to cut-off somewhere the inclusion of processes, leading to underestimation of the environmental impacts. Process based LCA and particularly in the attributional version focusses on one unit of output assuming a constant background economy. In these cases, the effects a change in technology (e.g. the electricity mix) has on other sectors is not considered. Likewise, the interactions of these changes on the of the technologies itself is not considered (e.g. producing solar panels becomes less carbon intensive the more solar cells are contributing to the electricity mix). Recently, it has been highlighted that PBA methodology needs extensions to also account for scenario analysis to assess future developments (e.g. policies or large scale transitions), see Gibon et al. (2015) for references.

Ex-ante/Prospective LCA

Van der Hulst et al. (2020) describe the ex-ante and prospective LCA approach as follows: “

“A specific strand of LCA is the one that does assessments of emerging technologies, studied at an early phase, and typically labelled either “prospective” or “ex-ante” LCA. Indeed, van der Giesen et al. (2020) regard these umbrella terms for the same exercise. However, they argue that the term ex-ante indicates assessment before market introduction of a technology, whereas prospective LCA can also be performed on established technologies to estimate future environmental impacts. In this paper we use the term prospective LCA and adopt the definition from Arvidsson et al. (2017) that “an LCA is prospective when the (emerging) technology studied is in an early phase of development (e.g., small-scale production), but the technology is modelled at a future, more-developed phase (e.g., large-scale production)”. As pointed out by Buyle et al. (2019), the term “emerging technology” has seen similar ambiguity. In this paper we apply the same definition as they adopted, which defines emerging technologies as “technologies that are still under development and are not ready yet to enter the market”.

2.1.2 Common applications of the approach

Life cycle assessment has been developed for comparison of specific products or services, including the technologies or processes needed to provide them. It is also widely used to identify environmental hotspots and improvement options within one product chain. The functional unit that is central to the analysis, all flows and inventories are related to that unit, that described the function to be provided. It can be a kg of product but also the provision of a function, such as stability or temperature control over a specific period. The underlying assumption in (attributional) LCA is that the provision of an extra unit of the function will not change the general economic and physical relations. Therefore, using attributional LCA to assess the impacts of substantial changes should be done with care, consequential LCA is advised for these cases. Likewise, traditionally, impact assessment methods are calculated for marginal changes. Most current assessment methods, however, go beyond this approach (e.g. lc-impact.eu). UNEP/SETAC life cycle initiative advises marginal methods for analysis where no substantial changes are expected, average approaches are advised for larger scale changes.

Due to the capability for benchmarking and hotspot analysis, LCA has often been used to guide technology development.

However, LCA results based on data from a technology under development are expectedly not representative of the impacts at full scale production and large scale implementation. Therefore, a new sub-family of LCA studies has emerged, referred to as prospective or ex-ante LCA. In this type of LCAs, diverse methods are applied to estimate inventories at large scale from lab data. Next to that, it is often taking account of changes that have occurred in the 'background' economy, such as changes in the energy provision-mix, when full scale production is reached. Finally, considering the larger degrees of freedom, also a specific treatment of uncertainty is called for (e.g. refs below).

2.1.3 Data requirements for LCA

This section will describe data needs of LCA in general (compared to other tools). Several software packages to build LCA models and databases for data gathering are available either on a commercial basis or open source. The general principles apply regardless of the specific choice in software and database, therefore they will be touched upon if necessary in the detailed sections.

To conduct a life cycle assessment data on all so-called interventions, i.e. resources extractions and emissions to soil, water and air along the product's life cycle are required. In general, part of these data relating to the foreground system (e.g. the specific technology under investigation) are collected by the practitioner and the interventions for many inputs in that foreground (e.g. energy, base material inputs) can be taken from existing databases. The most prominent European example of a process based database is ecoinvent.

2.1.4 Advantages and disadvantages

Table 1: (dis)advantages of LCA

Advantages	Disadvantages
Life cycle thinking	Comparative tool
Detailed technological knowledge can be included	Contribution to total emissions/demand only captures if the LCA is scaled up to total societal demand
Product focus	Data intensive
Accepted tool for policy applications, e.g. ecolabeling	static/linear tool/no time considerations / no disruptions -> less suitable to assess e.g. yearly reduction targets
Many impact categories	Cut-off and truncation
Great technological detail	Current/past data
	Is product-focused (see above)
	Economic relations constant
Specific for ex-ante/prospective LCAs	
Guide early stage technology development	Higher uncertainty
Include future/scenarios	
Systematic way to look/ guide future	

2.2 Input Output Analysis (IOA)

2.2.1 Short description of modelling approach

Input-Output Analysis originated in the 30s of the 20th century to assess major macroeconomic impulses into an economy. The modelling approach is based on

national accounts and linear algebra. The national accounts usually show the supply and use relations of products from (supply) and to (use) sectors. These relations, supply or use, are then translated in an overall input-output structure that usually describes how sectors interact with sectors in terms of production. When physical quantities are used, the result is a physical IOA instead of a monetary IOA. The accuracy of monetary based statistics is higher than the accuracy of recorded physical flows.

In recent decades, IOA has been increasingly used to assess major environmental impacts that result from major economic impulses, the so called Environmentally Extended IO analysis (EEIOA). The EEIO modelling approach has traditionally focused on assessing footprints of regions or sectors. Thanks to multiple advancements, EEIO database developers have made ever more comprehensive tables that include the entire global economy (e.g. in multi-regional EEIO) and other sectors. Such developments can be seen, for example, in EXIOBASE, EORA and FABIO databases, which through the years have increased their regional and sectoral resolution. The performance of EEIOA is often benchmarked against that of LCA, as they both aim to assess environmental impact, but from a distinctly different perspective. LCA looks at product-level or bottom-up approach, while EEIOA is a top-down approach. A disadvantage of the IOA is the uncertainty in translating monetary flows to environmental extensions. The level of detail is intrinsically lower than in process based LCA, making EEIOA less appropriate to model specific technologies or compare similar processes. Additionally, the number of extensions (like emissions and resource extractions) is higher in process based LCA. , i.e An advantage of IO models is that social-economic indicators, like employment, are included next to environmental ones.

2.2.2 Common applications of the approach

To assess impact of policy measures, IOA models are a common suite of models. It enables analysis of policy measures that are expected to have limited price effects.

Also, IOA is used to analyse:

- The socio-economic and environmental impacts from a consumption-based perspective by using the Leontief inverse.
- The hotspots impacts of specific supply chains.
- For circularity, it is usually used to assess the impacts of changes in primary/secondary material (i.e. substitution) and resource efficiency strategies see for example (Aguilar-Hernandez et al. 2018) and (Donati et al. 2020).

Figure 2 below shows how particular circular economy strategies can be assessed in the IOA framework (Aguilar-Hernandez et al. 2018). The figure indicates causal links between Products (P), Sectors (S), Waste streams (W) and Treatment activities (T). The green square with a solid border represents a “primary sequence”: an element of an EEIOA that can be adapted to represent the implementation of a circularity intervention. The red squares with dotted borders represent “secondary sequences”: indirect impacts in response to the primary stimulus. For both green and red squares, the up and/or down arrows (‘↑↓’) represent a relative increment and/or reduction of technical coefficients that can be increasing or decreasing in different sectors or industries due to the same causal link.

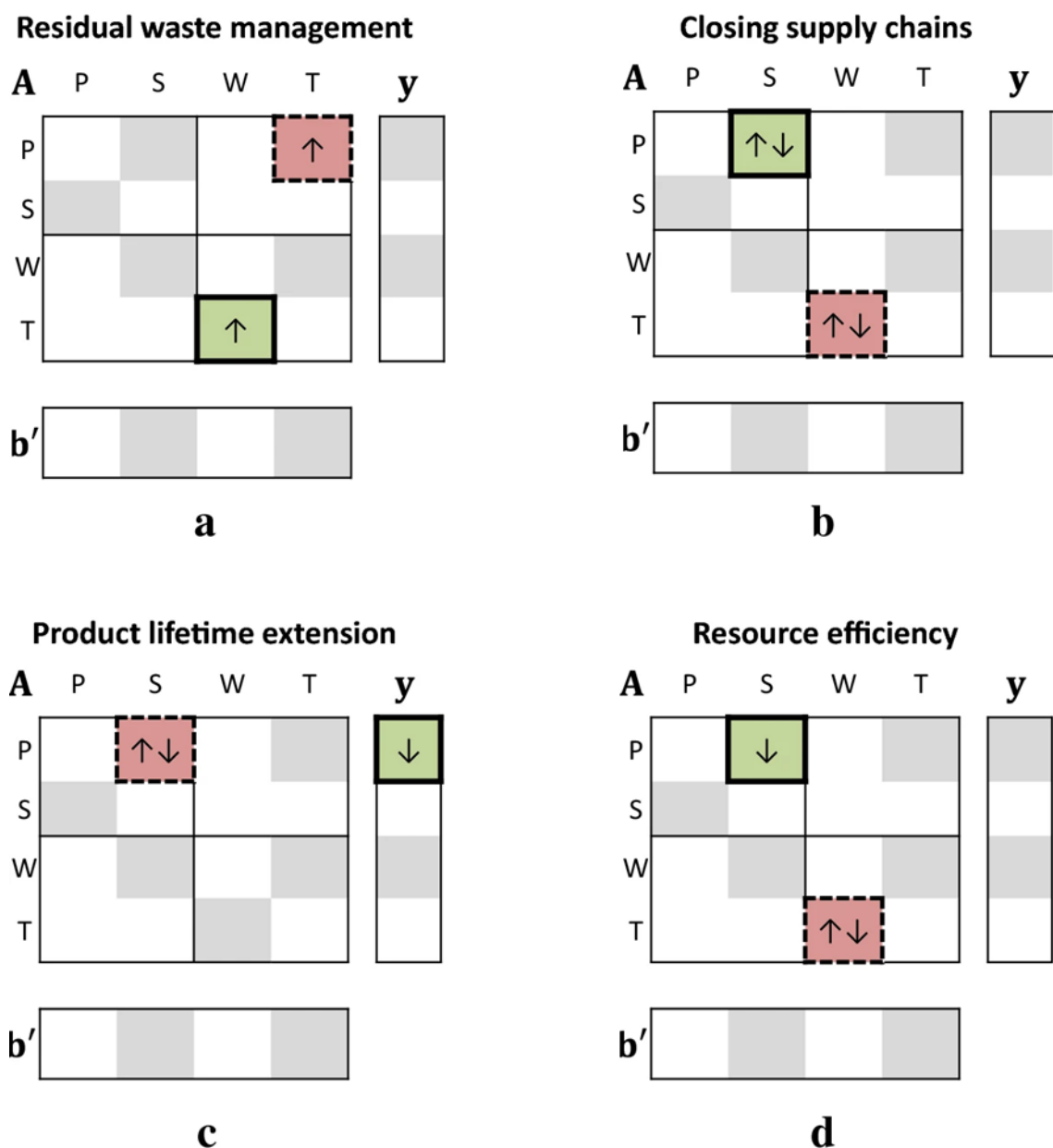


Figure 2: abstract scheme of Input-Output tables

2.2.3 Data requirements for IOA

National accounts usually suffice as the basic source of data. For MRIO models, it is noted that the data quality and granularity of different regions are important points of attention and sometimes concern. With diverging quality and granularity levels, harmonisation and balancing routines are required to prepare the data. These routines can represent a source of error.

2.2.4 Advantages and disadvantages

Table 2: (dis)advantages of IOA

Advantages	Disadvantages
Comprehensive in coverage of the total production and environmental pressures in the national (IO) and global economy (MRIO)	
	Differences in technologies invisible (low resolution in production)
Monetary units, which are recorded better than material units	Monetary units that are used as proxy of physical units assuming homogeneous prices for all sectors
	In general (compared to e.g. LCA) lower coverage of environmental pressures and impact categories
Allows to analyze production and consumption perspective	Usually limited time series, and up-to-date data
It includes socio-economic and environmental accounts	Lacking stock information
	Not suitable for assessing behavioural changes (as it is a non-dynamic model)
	Data uncertainty

2.3 MFA

2.3.1 Short description of modelling approach

This section will describe the economy-wide Material Flow Accounting that is aimed at dynamic i.e. time-dependant analysis. This so-called 'dynamic MFA (dMFA)' ensures stocks and flows of materials and products are modelled consistently over time (e.g. Hu et al., 2010; Wiedenhofer et al., 2019; Deetman et al., 2020). The dMFA approach has various parallels with Stock-Flow Consistent (SFC) models in macro-economics (Carnevali et al., 2019).

Material flow consistent modelling guarantees a correct and comprehensive integration of all the flows and the stocks of an economy. DMFA looks at materials and product flows in the economic system in a specific year, and which materials in the form of different products end up as societal stock. Conversely, dMFA also considers stock erosion, i.e. the products and infrastructure reaching end of life and flowing out of stocks as obsolete products, secondary raw materials, and waste. dMFA studies usually are done with a focus on specific materials (e.g. steel, see e.g. Pauliuk et al., 2013), specific products (e.g. washing machines, see Siguënza et al., 2021), but there is no impediment to perform dMFAs that comprehensively cover all material and product groups in the economy.

See for instance Pauliuk et al. (2019) for a comprehensive modelling framework, and Pauliuk and Heeren (2020) for an example of a software framework.

The consistency of the accounting is ensured using three matrices:

1. The aggregate balance sheets, with all the initial stocks,

2. The transaction flow, recording all the transactions taking places in the economy (e.g. intermediate consumption, final consumption, addition to and erosion from stocks);
3. The stock revaluation matrix, showing the changes in the stocks resulting from the transactions. The matrices are built respecting mass balance principles. Someone's inflow is someone else's outflows. Furthermore, each sector and the economy must respect their mass balance constraints. No materials or products can come from (or end up) nowhere.

An interesting future avenue of research would be to integrate the physical approach of the dMFA community with the SFC approach. The SFC approach incorporates in the (mass) Balance-Sheet (BS) and the Transactions-Flow Matrix (TFM) of the economy, providing the accounting framework SFC models' identities are derived from. In SFC, the BS encompasses sectoral assets and liabilities. The TFM is obtained by combining the national income equation with the sectoral flow of funds accounting. Receipts or sources of funds are usually recorded using a positive sign, whereas payments or uses of funds are given a negative sign. The latter displays the changes in the stocks at time t due to purchases of new assets (issues of new liabilities). Notice that changes in stocks' values due to changes in assets' prices are not included here. They are sometimes recorded as revaluation effects in a third matrix, named the Full-Integration Matrix (FIM), where each sector's net wealth at time t is calculated by adding capital gains (subtracting capital losses) to net wealth at time $t - 1$.

SFC and dMFA models are usually based on linear equations. However, they can be amended to incorporate non-linearities.

2.3.2 *Common applications of the approach*

dMFA is often used to build consistent stock-flow scenarios for future use of products and materials (e.g. Deetman et al. 2020). The main characteristic and advantage of the SFC approach is that it provides a framework for treating the real and the financial sides of the economy in an integrated way (Nikiforos and Zezza, 2017).

2.3.3 *Data requirements for MFA*

For stock-flow consistency, the accounting system must include stocks. While for instance physical IO tables (or economic IO tables) show comprehensively the flows of products (and with these: materials) in the economy, only stock addition in the form of capital formation is shown explicitly, but not the sector where such addition takes place, nor the erosion from existing stocks. The physical equivalent of a Social Accounting Matrix (SAM) is needed for an accurate stock-flow consistency. An MFA can also been developed which could use IO data, or a Stock-Flow consistent model which can include physical data on economy and environment.

2.3.4 Advantages and disadvantages

Table 3: (dis)advantages of MFA

Advantages	Disadvantages
Tracks all flows and the way they accumulate	Traditional statistical accounts often do not include an 'investment matrix', i.e. in which sector stock formation of which type takes place. In MFA, data mining for stock and flows is laborious
No unexplained parts of the model due to required consistency	Challenges in the estimation of model coefficients
Can be used to identify unsustainable processes e.g. prolonged deficit resulting in unsustainable stock debt	Only popularized recently after great recession
These models are based on sound accounting principles, which inter alia allow constraining models' dynamics without anchoring them to any preordained long-run supply-side equilibrium	
If dmFA would be combined with SFC models, this enables accounting for the process of money creation (and destruction), while including a variety of financial assets, motives, and agents	There is hardly any experience of combining the physical dmFA approach from Industrial Ecology with the SFC approach from economics

Combining dmFA with SFC models has the promise to create a bridge between dmFA and economic modelling. However, SFC models typically ignore the transformation of matter and energy that takes place due to economic processes and the environmental problems caused by this transformation. However, these physical aspects can be integrated showing physical transactions, and the changes in depletion and accumulation of stocks of different nature, as well as the damaging effects of climate change on capital and labour (Dafermos et al. 2017).

2.4 CGEM (Computational General Equilibrium Models)

2.4.1 Short description of modelling approach (text from Raihan 2004))

Computable general equilibrium or CGE models are numerical models based on general equilibrium theory, which is implemented in the form of a computer program. These models have a few features which make them powerful tools of analysis. Most importantly, they are multi-sectoral and, in many cases, multi-regional and the behaviour of economic agents (producers and consumers) are modelled explicitly through utility and profit maximizing assumptions. In addition, they differ from other multi-sector tools of analysis in that economy-wide constraints are rigorously enforced, e.g. expansion in one sector can usually only occur at the expense of another, given limited resources. Starting from some calibrated base, experiments are conducted by shocking the initial equilibrium, introducing distortions or removing existing ones, and observing the new equilibrium which results.

Distortions in an economic system will generally have repercussions far beyond the sector in which those distortions occur, and where the distortions are wide-ranging, general equilibrium is perhaps the only method which can capture the relevant feedback and flow-through effects. CGE can thus provide a precise numerical answer to questions related to the impact of numerically specified trade policies.

CGE introduces assumptions on:

- Market structure (perfect or imperfect competition).
- Production function.
- Representative household behaviour to maximise their utility ("use").
- Government behaviour.
- Substitutability between domestic and foreign products (Armington assumption).
- Investment and dynamics.
- Model closure (unemployment?).
- Social Welfare = Welfare of the representative household.

2.4.2 *Common applications of the approach*

A CGE is the model of choice when core concepts of general economic theory are to be analysed in the context of economic policy measures on a macroeconomic level. CGE can give answers when

- Impact assessment of sectors which are directly affected by a certain intervention.
- Interventions are clear in terms of quantitative goals (e.g. 20% recycled plastic used in food packaging).
- Impacts of (set of) sector(s) or product(s) affected by a certain measure should be greater than margin of error of data.
- Measure must be translatable in economic terms, as CGE has a monetary base.

Given efforts in the last decades, the environmental extensions that are available for CGE models present an opportunity to model policy interventions that try to incorporate externalities, such as environmental costs.

2.4.3 *Data requirements for model (Text from Raihan 2004)*

CGE models are based on a Social Accounting Matrix (SAM) database. A SAM describes all economic transactions in an economy, such as intermediate use along the value-chain, final consumption, investments, endowments etc. In principle, CGE calculates a subset of parameters that together with the SAM and imputed values for the elasticities can replicate the data of the reference year (baseline). The following are features of SAM:

- The main strengths of the SAM based approach are the comprehensiveness of the coverage of economic accounts, their inter-linkages and the consistency of the accounts (aggregate income must be equal to aggregate expenditure).
- A SAM is only a database, not a model. It can be as aggregated or disaggregated as desired, or as permitted by the data. It may focus on a particular sub-sector of the economy on the production side.
- An agricultural SAM may have 15-20 agricultural sub-sectors (e.g. major individual crops, food crops, export crops, processing, marketing etc.) and a smaller number from rest of the economy, e.g. industry, services etc.

It could include many household groups that receive incomes from the resources that they provide to these activities, and which consume the products of the activities. In other words, its design can be very flexible, depending on the focus of the study and availability of statistics.

- SAMs can be constructed at distinct levels. Besides the national SAMs, there are analyses based on regional SAMs and village SAMs. Even before a SAM is subjected to some form of behavioural modelling analysis, the statistics can be very revealing. For example, a SAM will show income levels generated by various economic activities, and their distribution to various household groups. Thus, it already illustrates a lot about how various economic sectors are contributing to household incomes and food security.
- The construction of a CGE requires **much additional information**, e.g. how various economic accounts would be linked, parameters describing how producers, consumers and other economic agents would react (supply-demand elasticities, substitution elasticities).

Example of a Social Accounting Matrix for an Open Economy									
	Expenditures								
	Activities	Commo.	Factors	Ent.	HH	Govt.	Cap. Acc.	ROW	Total
Activities		Gross output							Total sales
Commodities	Intermediate goods demand				HH Consum.	Govt. Consum.	Invest.	Exports	Agg. demand
Factors	Value added							Factor service exports	Factor income
Enterprises			Gross profits			Transfers			Enterprise income
Households			Wages	Dist. profits		Transfers		Foreign remitt.	HH income
Government	Indirect taxes	tariffs	Factor taxes	Ent. taxes	Direct taxes				Govt. revenues
Capital account				Ret. earnings	HH savings	Govt. savings		Capital transfers from abroad	Savings
Rest of the World		imports	Factor service imports		Transfers abroad	Transfers abroad	Capital transfers abroad		Foreign exchange payments
Total	Total Costs	agg. supply	Factor exp.	Ent. Exp.	HH exp.	Govt. exp.	Invest.	Foreign exchange receipts	

Source: Reinert, K. A. and Roland-Host, D.W. (1997), Adapted from Piermartini R. and Teh R. (2005).

Figure 3: SAM table of CGE

2.4.4 Advantages and disadvantages

Table 4: (dis)advantages of CGEM

Advantages	Disadvantages
The CGE models have the advantage that specific policy measures as proposed can be accommodated without simplification and aggregation vis a vis the relation between supply and demand. The classification can respond closely to the one the policy maker is used to. (Iqbal and Siddiqui (2001))	Quality of the data. The quality of the model is partly dependent on the quality of the data for an arbitrarily chosen benchmark year. Since there are always stochastic anomalies and extraordinary economic events associated with any one year of a time series, this will detract from the validity of generalization drawn from the model. In addition, the data matrices often go through various scaling process to force micro-consistency, introducing untraceable biases into the rows and columns. These biases will directly influence the parameters of a calibrated model. (Iqbal and Siddiqui (2001))
Using CGE-models not only has the advantage that general equilibrium effects are taken into account but also that the interaction of different measures can be studied. (Iqbal and Siddiqui (2001))	Choice of Parameters. In the CGE model, some parameters are determined on the basis of a survey of empirical literature, some are chosen arbitrarily, and the remainder are set at values which allow the model to replicate the data of a chosen benchmark year. Also, users of the simulation results have no way to assess the evidence supporting the choice of most parameter values. (Iqbal and Siddiqui (2001)) Results are sensitive to elasticities used, which are fixed for a particular situation. (Constant elasticity of substitution among exports of different origin), which have strong implication for the estimate of trade creation or trade diversion. (Raihan, S. (2004)) The sensitivity of elasticities makes it harder for CGE to anticipate major shocks that could be expected in societal transitions.
In a data-rich country, macro and micro data can be combined to construct a CGE model to generate quantitative estimates of the impact of adjustment policies. (Iqbal and Siddiqui (2001))	Choice of functional forms. In most of the CGE models, researchers use first order functional forms, in particular, constant elasticity of substitution (CES), which embodies restrictive assumptions about the structure of the industries being modelled, by imposing a single non-

	negative substitution elasticity across all pairs of goods in the aggregator. The functional structure strongly influences the results from a policy simulation. It is suggested that a preferred alternative would be to use flexible functional forms, such as the translog or normalized quadratic, which have enough free parameters to provide a second order approximation to any underlying preference or technology aggregator function, and consequently can represent all the relevant own- and cross-price elasticities derived from an arbitrary utility or profit function, without imposing prior constraints. (Iqbal and Siddiqui (2001))
The key technical innovation of CGEs is that they escape the constraints of linearity. A CGE model can be a much better representation of real economies than its linear predecessors. (Iqbal and Siddiqui (2001))	Calibration of the model. The reliance on one-year aggregated data makes the system incapable of identifying important changes that take place within a year. Moreover, the benchmark year may not reflect the normal structure of the economy. Two practical solutions: (1) Use averages of benchmark years (2) system-wide econometric estimation of CGE model. For the latter approach, data availability of e.g. prices is an issue. (Iqbal and Siddiqui (2001))
A general equilibrium setting is preferable when the policy experiment to be modelled affects simultaneously many countries and many sectors. (Raihan, S. (2004))	Static CGE model. In many applications, the models indeed apply to a single period which may range from a year to a lifetime. The introduction of dynamic behaviour in a CGE model is an attempt to incorporate the time dimension in policy analysis. Some modelers have established the time path through the “sequencing” of equilibria. Yet, the timing of factor augmentation is often arbitrary set, an equilibrium is assumed to occur in each period, rather than being empirically established. (Iqbal and Siddiqui (2001))
General equilibrium model can capture inter-sectoral linkage effects. (Raihan, S. (2004))	Neoclassical Theory. Extreme closure rules commonly adopted in neoclassical CGE models have proved less accurate. (Iqbal and Siddiqui (2001))
Partial equilibrium models neglect offsetting effects following liberalization and working through inter-sectoral shifts, factor price adjustment and exchange rate	Sensitivity and results. CGE applications often do not examine the sensitivity of their results to alternative parameterizations. Where performed,

changes. The CGE addresses these issues reasonably. (Raihan, S. (2004))	sensitivity analysis is usually limited to simply judgmentally changing a few key elasticities. Correspondingly, it is unclear how much the parameters should be changed to demonstrate the robustness of the results. (Iqbal and Siddiqui (2001))
The CGE allows considering consumption of all goods by the rest of the world thus allows to estimate income effect of non-reciprocal preferential treatment, which is not possible by partial equilibrium analysis. (Raihan, S. (2004))	The threat of lacking granularity. It is possible that the model will be implementing policy measures or shocks to the model that affect only a small part of a sector. The production structure of the sector does not represent that specific product for which the policy option holds very well. For example, mattresses are produced in the furniture sector. The production structure of the furniture sector is not very suitable for mattresses. (comment Hettie Boonman (2020)).
The “general equilibrium” character of CGEs reflects the interdependency of economic variables- the notion that every change affects a range of other elements in an economy. Ripple effects of policy changes need to be considered when governments consider their options. (Raihan, S. (2004))	
The utility of a CGE construct in understanding complex and sometimes unexpected interactions in an economy should not be underestimated (Raihan, S. (2004))	

The most important disadvantage of using CGEs in assessing CE policies is related to the lack of sectoral detail. Shifts towards circular economy may include small changes in only one product of a product-group. Input-output tables use aggregated product and industry groups. Therefore this level of detail is lost or even not available.

On the other hand, CGE represents important advantages. CGE is a model that finds a full equilibrium. Changes in the underlying data (scenario shocks) are able to bring the economy towards a circular economy (e.g. recycling initiatives, leasing structures). The model finds a new equilibrium given the increase in work in recycling and leasing sectors. Furthermore, a CGE is a flexible model, it allows to add modules and equations that are suitable for the situation. That is, to model a CE-economy, additional modules/ equations that are suitable for a circular economy can be included. An example is a module that includes a feedback loop from household-waste to industries.

2.5 Partial Equilibrium (PE)

2.5.1 *Short description of modelling approach*

In this modelling approach, and contrary to a general equilibrium-model, a complete model of the economy is not needed. Whereas this is a disadvantage when studying system-wide shocks, a PE model can be quickly tuned to answer policy questions that do not require the effect in the overall system (or economy).

To build a PE model, a set of equations is needed that represents a part of the market in study with its relationships and elasticities. Once in possession of the algebraic model describing the system under study, conclusions can be made from price or quantity shocks that can be introduced by for example adding additional demand of a product or a sudden price rise.

This in turn will result in repercussions in the system under study thus allowing the modeller to draw conclusions (although limited in scope since only a part of the economy is being modelled) on what are the general effects of such shocks. Typically, a PE system will have in the equations that describe the system cross-price responses that allows the relation between the different system equations.

Although the output of a PE model is not as comprehensive as a CGE model, it does provide quick answers to not so complex case-studies. More complicated cases of PE models can be found in literature, but such formulations follow the complexity of the case-study.

2.5.2 *Common applications of the approach*

Due to its simpler formulation PE modelling is well suited for analysing simple relationships between economic flows where the need to address the entire system is not present. This does not mean that PE modelling is a simple modelling approach, that it is simpler to build compared to its more complex CGE parent. In view of our efforts to model CE policies, PE modelling is often used to model the interactions of the primary and recycling sectors for an array of commodities. Some case-studies are included in the literature part.

In energy studies, PE modelling is often used as a tool to model the interactions between producers and consumers. It is not explicitly called a PE model in literature, but it is often referred to as such, due to the nature of the simplification of the modelled power market. In the case of a power market model, modelling can be done for regions or countries and by setting some boundaries from which power may be imported or exported. Naturally, the characteristics of the imported power are not modelled in detail as the domestic consumption. Hence, the usage of the "partial" terminology here.

2.5.3 *Data requirements for PE*

To build a PE model, equations are needed that describe the relationship between the variables in the scope of the study. The chosen mathematical formulations can be of a different nature whether linear or non-linear for as long as the relationship can be described. Cross-price responses or any other factors relating the effects of a change in variable A following a change in B are also needed. Cross-price responses can be obtained from economic literature whereas mathematical formulations must come either from economic theory or in the case of a material market from the relationships between material flows (primary vs secondary flows, etc). In the case of the modelling of a power market, marginal costs, demand

functions and other relevant parameters needed to describe the interaction between supply and demand.

2.5.4 Advantages and disadvantages

Many of the advantages and disadvantages of a Partial Equilibrium model are shared with a Computable General Equilibrium model. The few distinctions are mentioned in the table below.

Table 5: (dis)advantages of PE

Advantages	Disadvantages
Simplicity: a system can be quickly set up	Reflects only the shocks in the chosen system
Allows to analyse a portion of the market while maintaining the rest constant	Is not suitable to analyse economy-wide effects of shocks
Usually much higher in product and sector detail for the part of the economy covered as CGEs	
Cross-price responses are simple factors that are added in equations	Depends on the quality of the assumptions
	Does not include feedback loops from the larger economic system

2.6 IAM (Integrated Assessment Models)

2.6.1 Short description of modelling approach

Lotze Campe (2018) have described this modelling approach as follows: *“Integrated assessment models are simulation models and try to link, within a single modelling framework, main features of society and economy with the biosphere and the atmosphere. It offers therefore a unique analytical option to policy makers: to understand the impacts of human activity on the sometimes-enigmatic effects on eco-systems, agricultural soils, air, water bodies etc. The concept of ecosystem services (ESS) is known to many by name, but is hard to understand for the non-expert. Applying an IAM can clarify the relation between economic and social activity on one hand, and the planet that offers the ecosystem to support it on the other.*

Starting with a focus on the connection between anthropogenic greenhouse gas emissions and climate change, the agenda of Integrated Assessment Models (IAM) now includes aspects of land use, biogeochemistry, hydrology, demography, and health. The goal is to make more and more parts of the “Earth system” endogenous to the modelling framework. This is an ongoing process, in which major methodological barriers between scientific disciplines must be overcome. E.g. the optimisation mode of most economic models must be linked with process-based time-step models in climate or biogeochemistry research. Integrated Assessment is a useful way of approaching complex issues like climate change, which involve a range of problems, disciplines, stakeholders and time and spatial scales. Climate change is very much a multi-actor problem: those involved include emitters of greenhouse gases, those who make climate change policy and those who will be affected directly and indirectly by climate change.”

2.6.2 *Common applications of the approach*

The main clients of IAM include the national Government, the European Commission, international organizations, such as IPCC, UNEP and OECD, and the research communities. Typical questions for the IAM framework are: What are effective response strategies for climate change, going beyond global cost efficiency? What response strategies would be able to provide enough food for 9 billion people around 2050, while conserving biodiversity and the provisioning of goods and services by ecosystems? What levels of effort are associated with implementing currently formulated sustainable development objectives (SDGs/Planetary Boundaries)? Can multiple targets be achieved at the same time? (van Vuuren et al. 2015).

2.6.3 *Data requirements for model*

Most Integrated Assessment Models require data on GDP and population as their main drivers of change. Other factors such as costs for technologies and fuels can also be part of IAMs, just like policy related indicators such as historic- or expected carbon prices. An interesting source is represented by the site of Carbonbrief¹. This site is also a good demonstration of the policy relevance of IAM exercises, being a prime example of climate policy assessment.

2.6.4 *Advantages and disadvantages (text from van Vuuren et al. 2015)*

The main advantages and disadvantages of Integrated Assessment Models (IAM) are described in the table below. It is noted that the different components of an IAM (climate, geophysical, transport) will all have a range of advantages and disadvantages, that are not included in this overview².

Table 6: (dis)advantages of IAM

Advantages	Disadvantages
Strong focus on representing both the earth and human systems, in terms of physical indicators. The advantage is that this allows for an easier link with the drivers of environmental degradation and a meaningful representation of long-term dynamics. As a result, also human activities are preferably represented in terms of physical units (e.g. number of cows) than in terms of monetary units.	Not all sub-models of IMAGE contain an explicit representation of policy measures. For instance, emissions are determined by so-called emissions factors (EFs, Emissions = EF x activity); as these are abstract, the model is not suitable to evaluate the feasibility of emission reduction strategies. The management factor determining future agricultural yields currently also is abstract.
IMAGE is a simulation model (not an optimisation model), which makes it specifically suitable for exploring the full range of scenario analyses.	
IMAGE accounts for feedbacks from the environmental system to the socio-economic system. Examples are the feedback between demand and availability of Bio-fuels or e.g. the feedback between emissions,	Not all socio-economic feedbacks can be accounted for. E.g. there is no feedback on population growth or economic growth assumptions.

¹ <https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change>

² <https://www.pbl.nl/sites/default/files/downloads/pbl-2015-image-strategy-document-1797.pdf>

temperature and the demand for heating or cooling such as air-conditioning.	
IMAGE contains a balanced representation of the land-use/agricultural system and the energy system. The team also has a long tradition in coupling these two systems.	Not all the main linkages between the various issues are included. For example, there is no feedback from water scarcity to energy decisions.
The IMAGE model contains detailed representation of the variables that are useful in environmental assessments (e.g. emissions, land use, energy system). Therefore, a key benefit of IAMs is to assess trade-offs between policies. Assessment of resource- or circular economy policies will always be complemented with a perspective on the (side-)effects on climate- or bio-diversity related indicators.	Some IMAGE sub-models form part of one large model code implying that they can exchange information in every time step, whereas others are coupled via the exchange of data files (e.g. the way TIMER and MAGNET are coupled to the other models in the IMAGE framework). This provides more flexibility – but is also more risky in terms of model management and limits the ability to take any feedback into account.
A key component of the IMAGE model is its geographical coverage. It represents the human system for a large number of regions and includes a detailed grid for environmental system calculations	The IMAGE model has a limited representation of short-term macroeconomic dynamics. Currently, price-responses are represented in the energy system model, but any feedback on economic structure, for instance, is lacking. Economic feedback is represented in the coupled MAGNET (agro-economic model).

IAMs have a strong focus on representing both the earth and human systems, in terms of physical indicators. The advantage is that this allows for an easier link with the drivers of environmental degradation and a meaningful representation of long-term dynamics. As a result, also human activities are preferably represented in terms of physical units (e.g. number of cows) than in terms of monetary units.

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2.7 Hybrid LCA

2.7.1 *Short description of modelling approach*

A way to profit from the best of both LCA and IO approaches is the use of hybrid LCA where foreground³ details on a specific product/technology are modelled in a process-based manner and background information is taken from input output databases. Thereby keeping the detailed technology information, but also including the entire economy. Several levels of hybridization between PBA and EEIO exist. The hybrid LCA approach is an odd beast in chapter 2, as it is already a combination of two individual approaches.

In general three approaches to hybridization of LCA are described:

- Tiered; (more like process based LCA with IO for background at certain point)
- IO based; (more like IOA with product disaggregation at point of interest)
- Integrated (systems influence each other).

Each of them has their own challenges. In general, they are related to translation between physical and monetary units (in all cases, except if results in IO based LCA are expressed in monetary units), disaggregation of sectors and avoidance of double-counting. Integrated hybrid LCA is the newest, most sophisticated, but also most challenging approach to hybrid LCA.

2.7.2 *Common applications of the approach*

Hybrid LCAs are used when there is a need to assess impacts on a regional or (super)national level that are created by interventions to products and/or sectors that are defined below the level of detail of the IO or CGE data. Hybrid LCA is also used when the modeller estimates that LCA suffers from truncation errors and no LCI data are available to correct this.

Hybrid LCA is often used in cases, where there is financial data available, but no physical data, e.g. see Bergesen et. al. (2014). This is often the case for services required. Hybrid LCA can also be used to correct the truncation error in LCA or increase the level of detail in IO based LCAs (Agez et al., 2020; Arvesen & Hertwich, 2012; Wiedmann et al. 2011). Integrated hybrid LCA is particularly challenging in that it strives to include the changes in the foreground (i.e. system under investigation, often process based), into the background again (often IO based). This re-integration is relevant in cases where the foreground is related to such large quantities that it might affect economic relations.

2.7.3 *Data requirements for hybrid LCA*

The requirements for this hybrid approach are of course similar to those of the underlying models such as LCI data and IO data, monetary-physical translation, product-sector aggregation/disaggregation.

³ Terms often used in LCA: foreground and background (upstream + downstream): Foreground indicates the part of the system that practitioner models him/herself, e.g. construction wind mill or electricity generation. Background refers to the part of the system that practitioner takes from existing databases, assuming them to be appropriate/representative, e.g. delivery of steel.

2.7.4 Advantages and disadvantages

Table 7: (dis)advantages of LCA

Advantages	Disadvantages
Allows combination of coverage and detail	
	Monetary-physical translation
	Challenging to avoid double counting
	Product-sector aggregation/disaggregation
Product-oriented (allows high level of (technological) detail)	Product-oriented, the strength is also a weakness. Individual assessments are hardly oriented towards larger economic consequences.

2.8 Tabulated overview of characteristics

To provide an overview of chapter 2, the characteristics of the modelling approaches are summarized in the table below.

Modelling approach vs output of the model

Table 9: output per modelling approach

[illegible]

Modelling approach vs input to the model

Table 10: input per modelling approach

[illegible]

Fundamental principles of the modelling approaches

Table 11: overview fundamental principles per approach

Modelling approach	General description of approach	Explicit principles
CGE	Computing how an economy reacts (according to the model) to impulses from economy, policy, technology or another specific external driver.	Supply and demand can be in an equilibrium after a series of impulses, elasticities of consumption/trade/production, econometrically determined coefficient, use of statics, macroeconomic resolution suffices.
Partial equilibrium model	Same as CGE, provided that only a part of the economy can be analyzed without significant repercussions on the outcome.	Same as CGE
LCA	Measuring the potential impact of a product/process in a cumulative way, assessing all life cycle stages.	Accountability per component and production process step, concept of a life-cycle (opposed to use-cycle), summation, functional unit, comparative approach, large coverage of impacts
(p)IO analysis	Accounting how national statistics describe the interdependence between products and industries.	Based on system of national accounts, matrix algebra, double entry bookkeeping; output equals demand; requiring total expenditure to equal total Income, macroeconomic resolution of typically between 30 and 150 sectors.
MFA	Describing the input and output of monetary and physical flows of materials in certain geographic entity (region, nation, world etc.).	General laws of natural science are obeyed (e.g. mass and energy can't be created or destroyed, you can't change a state of a system without adding exergy etc.)
IAM	Combining core characteristics from society and economy with the biosphere and atmosphere within a single analytical framework.	The planet provides eco system services that are inextricably part of human society, an economic production function

3 Assessing the need to combine modelling approaches

With the introduction of modelling approaches in chapter 2, we now want to see which modelling approach could be used to tackle certain policy relevant research questions.

3.1 Taking the policy maker view

The key research question of this study was formulated as follows: evaluate how relevant CE policy issues can be modelled and policy questions answered using (a range of) quantitative modelling approaches, or combinations of such approaches. Almost self-evidently, the interest of policy makers leads to a broader interest in the outcomes of measures and consequences of targets than just the impact on the emission of greenhouse gases and other environmental impacts. The relation with the impact on other sectors, on the broader economy and on employment is of importance to any policy maker.

A study from (Beaussier et al. 2019) highlights certain requirements for embedding modelling approaches and modelling research questions in the policy making process:

- Authority: it should be clear to individuals how their organisations can take the actions envisaged in the modelling exercise.
- Causality: the link between means, activities, achievements, and effects should be explicitly discussed and described.
- Target operationalisation: the much-used SMART criteria (Specific, Measurable, Acceptable, Realistic and Time-bound) should be applied when modelling a set of policy actions with their corresponding targets i.e. achievements.

We can therefore test the modelling approaches to see to what extent they meet the above-mentioned requirements.

3.2 An approach through case-studies

Applying the requirements from the previous paragraph, we have developed a set of case-studies that should be able to highlight the strengths and weaknesses of individual modelling approaches and the additional strengths obtained from combining two or more modelling approaches.

By taking the policy question as a starting point, we try to emulate the thought process of the non-expert that simply wants to explore the options when designing a policy evaluation process.

We suggest the following case-studies in an overview with all the modelling approaches, opposed to already linking a specific question to a specific approach.

- i. Case study 1: How ambitious can an EU country be in setting net outflow goals of critical raw materials? This case deals with target setting by authorities.
- ii. Case study 2: Introduction of lease services (servitization model), creating new links between several manufacturing sectors and service sectors. What will be the impacts of shifts from manufacturing to service providing in the final consumption of certain goods? The detailed case specifically is aimed at the material requirements in the servitization of transport.
- iii. Case study 3: How can the target of reducing primary raw material input in the construction sector in 2030 by 25% be met? What are the broader impacts on embodied CO2 emissions and economy of such a target?
- iv. Case study 4: How can a better standard for MPG ("Milieu-Prestatie-Gebouwen") stimulate use of wood in construction? What are the integral effects of specific targets on the use of primary or secondary materials in the construction sector?
- v. Case study 5: What are the integral consequences if X% of plastics are either mechanically or chemically recycled?

In the next section we will analyse how individual modelling approaches deal with these policy relevant questions.

In section 3.4 we will combine modelling approaches in order to analyse whether such combinations deliver additional value.

3.3 Case studies framed against the individual modelling approaches

Perspective from...	Is it possible to implement this measure and describe progress with this model alone? <i>Yes/No + reasoning</i>	What other model/ module/ data/ etc. would you need to describe the progress of implementation of this measure?	What type of outputs are to be expected?
Case study 1: How ambitious can an EU country be in setting net outflow goals of critical raw materials?			
CGE and PE	No , critical raw materials are specific products that are not part of a SUT or SAM framework.	We need story paths with assumptions on * Which type of critical raw material input should be reduced * Targets on the reduction, including the extra (preferably sector specific) costs of applying circular strategies that can retain the critical materials. Only if these costs are significant, CGE-modelling is preferred. Also: * How should measure be reached? Using behavioural changes or via policy measures (e.g. taxes)? * Other model that implements the specific measure for a detailed product/ material group. Spill over effects can be calculated using a CGE.	(Spill over) effects on household consumption, production, trade, consumption, employment. GHG emissions, price effects.
LCA	No, the use of a sector wide model is preferred here.	would need to know by which technologies this is achieved	will always show trad-offs if technologies are known
(p)IOA	Partly , there is a way to link critical raw materials specifically to products groups that are traded between sectors and regions in s IOA. Many CRMs are missing from most EEIO databases, having said that Exiobase for instance has a few categories that are represented.	LCI data is needed to see which product groups contain which raw materials. Moreover, trade data is needed on a very granular level to assess the imports and exports flow of the IOA. Lastly, the IO need to be discerned into relevant geographic regions.	Use and final consumption of product groups in certain years. Quantitative amounts of critical raw materials in those used or consumed final goods.
MFA or IAM	No, currently the level of detail in the manufacturing/industry sector of IAMs is too low to provide any meaningful insights on the material use.	Detailed modelling of demand of physical product flows (both inter-industry and to final demand) would be required.	Comparison of in- and outflow, environmental footprint of critical raw material extraction and recycling

Perspective from...	Is it possible to implement this measure and describe progress with this model alone? <i>Yes/No + reasoning</i>	What other model/ module/ data/ etc. would you need to describe the progress of implementation of this measure?	What type of outputs are to be expected?
Case 2: Introduction of lease services (servitisation model), creating new links between several manufacturing sectors and service sectors			
CGE and PE	Partly, only when database includes trustworthy data on leasing sector or when leasing product is not too specific (an aggregated product group).	Option 1: Extra information/ data on production structure of leasing sector. Option 2: Connect to model that is able to implement measure on detailed level. CGE can be used for additional spill over effects. This also requires additional information on the monetary size of this product relative the monetary size of the aggregated product group/ industry that it belongs to.	(Spill over) effects on household consumption, production, trade, consumption, employment. GHG emissions, price effects. When the effect is reached using policy measures (e.g. tax incentives, the increase in taxes is also output).
LCA	No, business models are not part of an LCA. Only indirectly would product design or other CE-strategies resulting from implementation of a servitisation business model be part of an LCA	A economic or business behaviour imitating model.	Can compare more service-based fulfilling of function to original product, cannot capture trickle to other sectors
(p)IOA	Partly, only when sector granularity offers at least rental and lease service explicitly	Prices and preferences matter a great deal when assessing services and the value that consumers experience from these services. This information should come from CGE or PE models.	Economic value because of shifts in raw material use per sector and the whole economy, compared to the economic value generated in a business-as-usual sector/economy (scenario comparison) and other regions.
MFA or IAM	Partly, only limited to a shortlist of products. Now this is only possible for cars, furniture will be possible in the near future (ongoing work).	General data on the effect of leasing on product lifespan would still be required.	The size of the vehicle fleet in a particular economy, timeseries of emissions, cumulative raw material demands

Perspective from...	Is it possible to implement this measure and describe progress with this model alone? <i>Yes/No + reasoning</i>	What other model/ module/ data/ etc. would you need to describe the progress of implementation of this measure?	What type of outputs are to be expected?
Case study 3: How can the target of reducing primary raw material input in the construction sector in 2030 by 25% be met?			
CGE and PE	Partly , only when the goal is less vague as currently stated and rooted in reality of increasing building sector.	We need story paths with assumptions on * Which type of primary raw material input should be reduced * Targets on the reduction Also: * How should measure be reached? Using behavioural changes or via policy measures (e.g. taxes)?	(Spill over) effects on household consumption, production, trade, consumption, employment. GHG emissions, price effects.
LCA	No, the use of a sector wide model is preferred here.	would need to know by which technologies this is achieved	will always show trade-offs if technologies are known
(p)IOA	Partly : it would leave questions unanswered about the possibility to extract certain primary building materials from nature and how this goal relates to required building stocks to meet societal needs.	Scenarios are needed that are benchmarked against stock-flow data. IAM data might offer information on the natural resource stocks that are expected to be used for the sizeable flows in construction	(Spill over) effects on household consumption, production, trade, consumption, employment. GHG emissions, price effects.
MFA or IAM	No, this can only be studied using a detailed model on global construction material requirements. Such a model is not available		Substitution effects of construction materials such as wood, concrete, steel, brick, and glass can be accounted for both in terms of annual material demand as well as physical volumes in stock and waste-flows.

Perspective from...	Is it possible to implement this measure and describe progress with this model alone? <i>Yes/No + reasoning</i>	What other model/ module/ data/ etc. would you need to describe the progress of implementation of this measure?	What type of outputs are to be expected?
Case study 4: How can a better standard for MPG ("Milieu-Prestatie-Gebouwen") stimulate use of wood in construction?			
CGE and PE	Yes , when the goal is(or would be) quantified regarding the actual wood demand.	We need: * Story paths with assumptions on the effect of MPG on the use of wood.	(Spill over) effects on household consumption, production, trade, consumption, employment. GHG emissions, price effects. When the effect is reached using policy measures (e.g. tax incentives, the increase in taxes is also output).
LCA	No, a comprehensive LCA (overall efficiency, trade-off between use phases, different purposes from one piece wood etc) that incorporates all aspects of a log i.e. a piece of wood could do analyse the outcome, but not answer the 'how'.	Social science contributions would be required.	LCA can show how diverse wood options influence MPG
(p)IOA	No , the detailed implications of the MPGs are beyond the measure of the IOA. The only thing that could be modelled, is a change of the standard or if one expects technological changes in the construction sector. Those could be modelled in IO by shifting suppliers and substituting materials.	LCA information that can put the MPG of the construction phase into context with the use phase. Moreover, we need an IAM to assess the sourcing options of wood.	Share of wood in production of building materials and the effect on the overall footprint of a building.
MFA or IAM	Yes, in IMAGE this is currently possible as an ex-post analysis of the material model for buildings. Another example of such analysis can be found in the IRP RECC ⁴ study.	Integration between materials & energy modelling in IMAGE would be required.	Expected outputs could be the avoided emissions through substitution of steel and concrete, but also the carbon storage potential (CSU) of wood used in buildings, normalized to annual use of wood.

⁴ <https://www.resourcepanel.org/reports/resource-efficiency-and-climate-change>

Perspective from...	Is it possible to implement this measure and describe progress with this model alone? <i>Yes/No + reasoning</i>	What other model/ module/ data/ etc. would you need to describe the progress of implementation of this measure?	What type of outputs are to be expected?
Case study 5: What are the integral consequences if X% of plastics are either mechanically or chemically recycled?			
CGE and PE	No , only a combination with (physical) input output data would be able to evaluate this question.	Option 1: Extra information/ data to disaggregate the plastic recycling sector into two sectors: mechanically/ chemical recycling. Option 2: Connect to a model that implements this measure on a detailed level, such as an aggregated LCA or detailed (p)IOA. The “shock” to CGE is applied to the aggregated sector level of the CGE.	(Spill over) effects on household consumption, production, trade, consumption, employment. GHG emissions, price effects. When the effect is reached using policy measures (e.g. tax incentive or cost-incurring regulation), the increased impact on demand in related sectors and changes in taxes are expected output.
LCA	No, integral consequences include outcomes related to investment and employment, which cannot be delivered through LCA. ?????Yes, if a baseline and ratio between flows is assumed, also looking at replaced products requires additional assumptions	To know a total amount (e.g. plastic waste in NL per year), the national flows are required. Secondly, LCA answers questions compared to a baseline, here f.i. incineration can be considered as the baseline. Third, as not all plastic types can be both chemically and mechanically recycled and lead to useful recycled material flows, relations between plastic type and the possible recycle route are required to make sense of the % (mechanically/chemically) recycled plastic	A change in environmental impacts compared to a baseline, this can be relative, e.g. for one kg of plastic waste of certain composition that allows both treatments, or for total flows. Underlying assumption here is that change in total flows, not changes the economic structure.
(p)IOA	Partly , but only in case the IOA granularity allows for secondary plastics flows and a physical IOA is required	To assess this question with a (p)IOA, it is inevitable that detailed information from an LCA is required to adjust the coefficients and/or extensions. A MFA could also provide useful information, particularly on the expected rate of change between types of plastics over the years.	Level of raw material inputs and evaded environmental impacts for certain target years. Also, socio-economic performance of the change in comparison with the baseline.

Perspective from...	Is it possible to implement this measure and describe progress with this model alone? <i>Yes/No + reasoning</i>	What other model/ module/ data/ etc. would you need to describe the progress of implementation of this measure?	What type of outputs are to be expected?
MFA or IAM	Not yet, but work is ongoing, e.g. by Paul Stegmann ⁵ .	Expansion of plastics demand modelling. A detailed plastics production and recycling module.	Full overview of resource and energy use required for plastics production, including assessment of recycling and waste-flow oriented policies.

⁵ <http://programme.eubce.com/2020/abstract.php?idabs=17460&idses=1029&idtopic=24>

4 Combining models to answer policy relevant questions

In chapter 3 we assessed the potential of individual models to provide relevant insights for policy makers on the basis of five cases. Generally, we can conclude that individuals models provide only partly, rough or no answers to the policy issues raised in these cases. In this section, we will explore the option to combine modelling approaches that are novel. We will assess whether these combinations might be suitable to model elements of a circular economy transition and can counter the disadvantages of individual approaches.

The cases discussed in this section are partly rooted in literature data. They are in principle closely linked to the cases that were introduced in the previous section.

Two additional 'cases' are discussed at the end of this chapter; it concerns a generic case about monitoring waste flows within a framework of macro level accounting. These cases are not directly related to a specific policy question, but offer a view on relevant combinations of approaches that make them worth their

4.1 Case 1: how ambitious can an EU country be in setting net outflow goals of critical raw materials?

Critical raw materials have been on the European policy agenda since the Raw Material Initiative from 2008⁶. In a broader context, they have been part of academic research since the Club of Rome report from 1972. Policy questions regarding security of supply and depletion of natural critical raw material resources come and go depending on the economic and political situation on the geopolitical stage.

In the Netherlands, TNO has attempted to link thousands of product groups that are part of the Harmonised System/Combined Nomenclature (HS/CN) classification of the UN. The PANORAMA project will provide a robust scientific base to the approach of identifying substances.

The policy target that is the subject of this case is the aim to avoid net outflow of critical raw materials by 2030 from the Dutch economy. The target is part of the Manufacturing transition agenda as published January 2018. The nature of the "zero-net-outflow" target illustrates the difference between a policy target and the multitude of policy issues that are related to this target. Examples of these issues are responsible sourcing, enabling circular strategies for CRM-containing products, investing in strategic autonomy, or increasing delivery time stability.

The macro-economic nature of the research question should be combined with specific product-level options. We will therefore combine two modelling approaches: Input-Output Analysis and LCA. The approach is nevertheless different from hybrid IO-LCA in terms of product scope.

⁶ <https://publications.jrc.ec.europa.eu/repository/handle/JRC105697>

4.1.1 *What outputs are required*

To model the flow of critical raw materials, an economy-wide approach is needed to link and quantify critical raw materials explicitly to the product groups in that entire economy. It is essential that import and export data are available of the product groups. This will make explicit in which shape critical raw materials enter or leave the Netherlands economy. And will make it possible to compile the net flow of critical raw materials as an indicator.

The required output is an estimate of the total flow of critical raw materials of a country, in this case the Netherlands, as raw material or embedded in intermediate or final products. For this, a baseline scenario to estimate future use is required. The amount embedded in products, mainly if imported, may require alternative sources, such as LCAs or specialized scientific literature. Official statistics cannot provide this level of information. This estimate is preferably based on public statistics and the output can be obtained in future studies. It would be preferred if the research effort could be cumulated by making sure that the identification of critical raw materials in product groups is based on public data and documented in a transparent manner. An example of such a statistical classification, that is detailed enough, could be the Harmonized System/Combined Nomenclature of the United Nations.

The required output should make individual chemical elements/raw materials explicit.

4.1.2 *Which shortcomings are experienced if the measure/policy is assessed with a single modelling approach?*

If one would assess the flow of product groups at face value, it would be impossible to know the presence of certain chemical elements in these products. Raw materials are easy to spot, as are product groups that still contain the name of the chemical element.

For example, "products of Niobium", that comprise of wires, sheets etc. of 99,9% Niobium. But the use of metals in products down the supply chain gets more complicated and obfuscated quite rapidly. Especially the presence of minor metals, such as Co, W, In, Re and Mo, is beyond the knowledge base of every statistician or macro-economic modeler.

If one would assess the presence of critical raw materials from a Life Cycle Inventory (LCI), it would be easy to ascertain the presence of a certain material. Even 'the quantity of' is normally part of the LCI. The level of detail of these LCI are however high, which makes it hard to transfer results and conclusions to economy wide models without combining the LCI with other modelling approaches. Even though import and export statistics are reported on a detail level that describe the entire economy in just under 10.000 product groups, the LCI data pertains usually to products more detailed to the trade statistics level. Assessing the flows of materials based on LCI alone is impossible, as these data do not contain annual sales or use of this product.

4.1.3 *What other modelling approach do you think you need, to be able to monitor or evaluate the implementation of the policy/measure?*

Linking the LCI information to the macro-economic level, which is vital if one needs to know the net in- or outflow of the critical raw material of a specific product(group) or groups. The combination of the modelling approaches Input-Output Analysis and

LCA seems the most promising way. Important to note, product groups as described by the HS/CN classification are part of the IOA, as this is the trade statistics that normally provide the National Accounts of any country with the import and export data.

A combination between IO representing the macro-economic level, and LCA could be made. The quality of the macroeconomic data would determine the relevance of this combination. If the data is based on dedicated research into certain products used in society, results of the IO macro level might offer a validation of the results found by using trade statistics in the IO approach. It seems however a challenging task for a model to cover the entire economy by these possible (alternative to trade statistics) data sources.

Another combination could be found in an integrated hybrid IO-LCA analysis. If efforts are made to update the IO extensions to accommodate the presence of certain metals, it could well be that this modelling approach provides modelling outcomes that can be compared with the combination of IOA and LCA.

Reflecting on the combination of IOA and LCA, we give the following assessments on the three recurrent questions about applicability.

Does the combination of models enable impact assessment of a certain quantified target in the future?

Yes, by mapping the use of chemical flows into sectors, it is possible to evaluate who and what is affected/should be targeted by policy measures.

Does the combination of models enable impact assessment of individual policy measures starting in base year?

Only when a generic macro-economic policy action is aimed at the use of a particular raw material.

The analytical strength of the combination is aimed at better understanding the relation between products and raw materials. Effects of policy measures that do not have a direct relation with a specific raw material might just as well be analysed with regular IOA. But in any case, the combination of top-down (IO) and bottom-up (LCA) delivers more consistent analytical tools even at macro scale. The approach here is that policy impacts are represented in the different options that are compared in the LCA.

Does the combination of models enable impact assessment of the maximum (using reasonable assumptions) impact of constraint on a certain indicator for instance CO₂ (potential study).

Possibly. When a physical maximum should be assessed that (again) is explicitly related to a specific raw material, for instance the supply of that material, the impact of that restraint could be analysed using this combination.

4.1.4

What examples of combining modelling approaches can be found in literature?

The PANORAMA⁷ project aims to identify critical raw materials in trade statistics. A direct result is the opportunity to produce flows and even stocks of the particular metal. Another result is that EXIOBASE product groups can be extended with the

⁷ <https://eitrawmaterials.eu/project/panorama/>

presence of these metals (just as these product groups are extended with emission coefficients and other use of natural resources), effectively representing the combination of modelling approaches discussed in this case study.

The JRC has published a method to assess criticality of raw materials (Blengini et al. 2017). The relevance to combining IO data, trade data and LCI is their suggestion to link economic importance to LCI's and other bottom-up sources that confirm the use (and an estimate of the quantity of use) of a certain raw material in an economic sector.

4.2 Case 2: Assessing material requirements of policy options in the servitisation of household (or personal) transport

This case concerns the assessment of impacts of policies concerning the Introduction of servitisation of transport equipment for households. These services are guaranteed to create new links between several manufacturing sectors and service sectors. To focus the case study, we will consider the automobiles for up to 9 people as the product of interest. Other transport equipment such as (mini)buses or the range of novel electric open-air vehicles for multiple persons are not included. The innovative character of some of these vehicles provides a case study of its own about product and sector definitions.

The definition of the circular economy is often and incorrectly reduced to material flows and strategies to link material flows before and after a use phase of a product. This simplification is troublesome because it overlooks the fact that value retention and utility are vital concepts in a circular economy. This case-study is about the circular strategy that aims to maximize utility to consumers whilst using professional deployed resources to retain value: servitisation.

The fact that an average personal car is used by a household for only around one hour a day (Shancita et al. 2014) is often touted as evidence that the stock of cars ("motorized transport equipment for households for over 2 persons") can be reduced if servitisation business models would be employed. These business models have in most cases many links to sustainability policy areas such as the management of public (parking) space, supplying energy to vehicles, taxing emissions and taxing ownership of vehicles. To actually deliver the assumed potential to reduce the number of vehicles in use, circular economy policy makers should have accurate macroeconomic information about vehicles in society and the mechanics of the use of these vehicles.

Examples of these mechanics are the amount of person-kilometres, the number and value of vehicle purchases, some specific properties of vehicle stocks in society, prices of vehicles or energy carriers and prices of lease or rental or transport services delivered by enterprises. National statistics describe these mechanics which makes IOA the logical model to deploy them, since this model is based on national statistics. The requirement for "mechanics" is especially relevant given the many available underlying databases that are managed by institutions (detailed vehicle registrations, vehicle performance, driver performance). These underlying databases could be linked to base the creation of sensible policies on. Annual information linked to an input output table offers the starting point for all the

mentioned data and information. Consequently, stocks can be estimated using additional techniques from MFA approaches.

4.2.1 *What outputs are required*

To assess the impacts of effective policies to develop servitisation, it is necessary that models provide output that relate to the annual number of vehicles that enter the market, the number of vehicles in stock in society, the amount of “person-kilometres” and the propulsion type of these vehicles. The only way for a IOA to produce such outputs is via a link with specific information in a MFA.

Answers to the following policy questions on a national level are deemed relevant in this case-study: what would be the required amount of subsidy for a certain servitisation support scheme? what would be the effect of increased use on the monetary scrap rate for these vehicles (an indicator for the speed with which vehicles are “removed from market”)? What are the embedded materials (in shape of components mostly) in these vehicles? What are the upstream effects and downstream effects on other sectors of different consumption of passenger-kilometres? Passenger kilometres are notably different from the “number of cars” variable, in an increasingly circular economy that aims to reduce the idle time of vehicles.

The upstream and downstream impacts could be for example different use of components from other (non-vehicle manufacturing) sectors, use of cleaning services, use of data management services, deployment of professional drivers, different use of plastic and metal components, close monitoring of innovative components to compensate for teething pains. All of these impacts in sectors, other than car manufacturing, could be linked to stocks and flows of vehicles. It is important to note that the abovementioned impacts signify the difference between policy questions that pertain to the energy transition or to the circular economy transition. This distinction matters to the organization of public policy, the distinction is much less relevant from a technical perspective. The uptake of electric vehicles and the shift in goods and services to support the electric vehicle stock is best considered as a part of the energy transition policy package. The purpose of circular economy policies is to add perspectives to maximize and retain value of the materials involved, by understanding which goods and services enable that value maximization. The consequences of possible circular economy policies such as changing lease legislation or taxation on the material vehicle stock is what this case study should deliver as output. Note that the efficacy of these policies is assumed to be certified and that the model application cannot shed light on how to attain this efficacy by influencing behaviour.

4.2.2 *Which shortcomings are experienced if a measure/policy is assessed with a single modelling approach?*

It is well possible to map the vehicle stock and sales of a certain country based on direct data, without using any model. The material component of vehicles would be represented when data on composition of vehicles is added to the registrations of sales and stocks. There are however two reasons why such an approach would be insufficient to steer circular economy policy. Firstly, a model needs to provide the information that allows to build value chains based on supply and use of raw materials and intermediate products. It is expected that indirect effects of vehicle sales will be significant given the many and specialized supply chains related to

cars. Secondly, a macroeconomic model is likely to be able to provide production and consumption perspective outcome. The ability of a modelling approach to calculate a consumption perspective i.e. footprint calculations is important for a circular economy transition. Where climate change related emissions are expected to focus on territorial policies following the UNFCCC guidelines to account for emissions, the circular strategies can and should have a global scope, i.e. consider the value chain.

4.2.3 What other modelling approach is feasible to implement this measure?

First, we look at what (p)IOA brings to the combination of modelling approaches. The typical input-output qualities are demonstrated in the calculation of the emissions associated with the materials used in the life cycle of the car. To calculate emissions of material use, an identity matrix “A” and emission coefficients are used. It can then be considered to change the intensity of use of vehicles due to higher occupancy of vehicles, by a factor typically between 1 and 4 expressed in person-kilometres. This is also suggested in (Allwood and Cullen, 2015, p271). In the (Donati et al. 2020) study they halved the transactions of cars to final demand. They assume that with an increase of vehicles mileage and occupancy we also have a reduction of urban public transport use. The ratio of urban-transport-use to shared-vehicles is 1:3 meaning that for every 1€ reduction on sales of personal vehicles due to sharing, 0.33€ are lost also in public transport (Donati et al. 2020). They also assumed that a third of vehicles would put this action into practice, applied both at a final consumer and intra-industry level.

Figure 4 gives an illustration how and where changes to the identity matrix A and the final demand vector are expected.

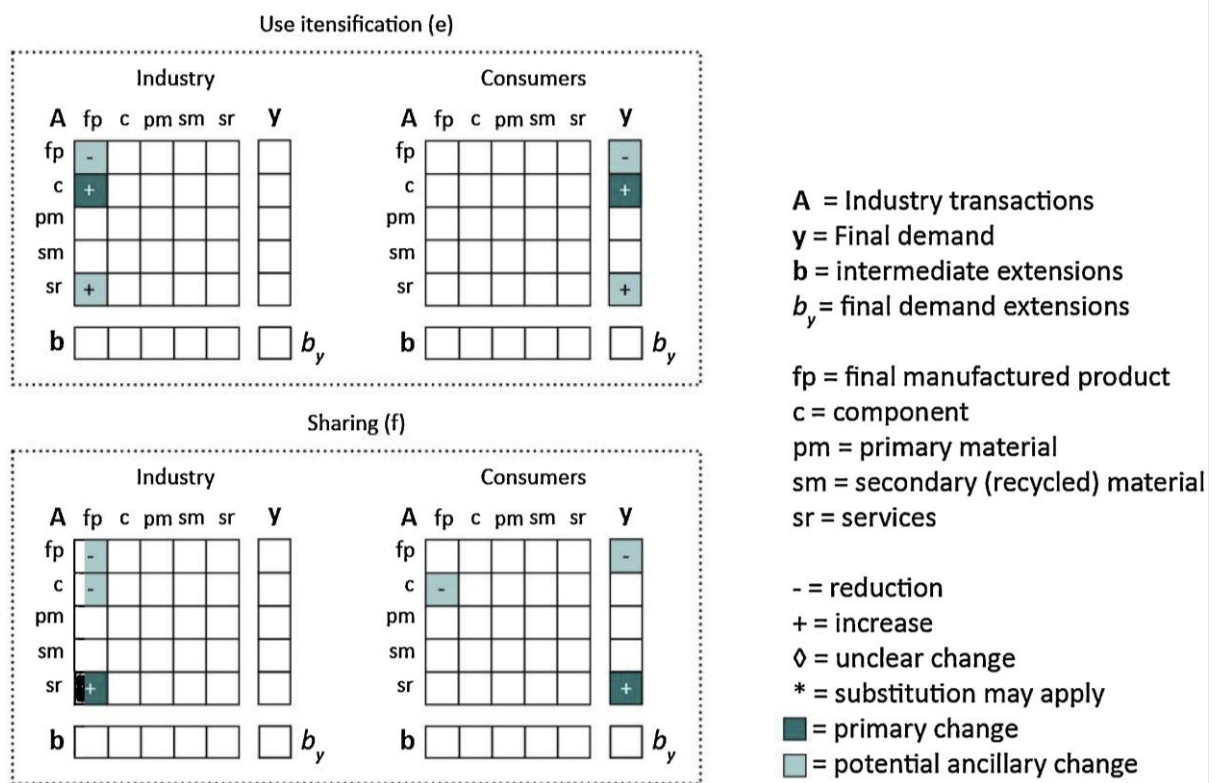


Figure 4 Changes in Input-Output structure of servitisation (use intensification or shared use) of vehicles.

We can then look at the addition of MFA equations. The MFA can use a commonly used Weibull distribution to model the stock, such as equations (4) and (5) in (Nakamoto et al. 2019). Additional equation can incorporate the number of vintage passenger cars, the fuel consumption of passenger cars in a certain year.

To aim the (Nakamoto et al. 2019 study) towards other impacts than GHG-emission, the variables need to be changed. The indirect emissions from deploying new vehicles is given by equation (11), as shown below. The μ_c and λ_c represent the stock and the fuel efficiency in a given country "c", the e_t vector represents the GHG emissions in year "t". These variables should be changed to other extensions or differently shaped identity matrices to model circular economy relevant policy interventions.

$$Q_{c,indirect}(t; \mu_c, \lambda_c) = e_t(I - A_t)^{-1} f_c(t; \mu_c, \lambda_c) \quad (11)$$

The combination of (p)IOA and stock-flow modelling offers no (extra) possibility to model the mechanics of prices. It is conceivable that a better combination would be to link the stock-flow with a CGE. It would better allow to model dynamic features and endogenous inclusion of price dynamics, investment and tax relations. IOA, in its various forms, is a static structural model which provides a high resolution of sectors and structural economic composition. This makes IOA a useful tool for the impact assessment of supply-chains (de Koning 2018).

Reflecting on the combination of IOA and MFA, we give the following assessments about on the three recurrent questions about applicability.

Does the combination of models enable impact assessment of a certain quantified target in the future?

Yes, the models allow to assess time series and change variable values per individual year.

Does the combination of models enable impact assessment of individual policy measures starting in base year?

Yes, the combination of annual flows and stocks offers pegs and the "consumption" of passenger transport services to the number of vehicles in society. This effect can be assessed in a forward-looking modelling approach that singles out an individual policy measure.

Does the combination of models enable impact assessment the maximum (using reasonable assumptions) impact of constraint on a certain indicator for instance CO₂ (potential study)?

When it is possible to determine a certain optimum to a stock or flow, it will be possible to assess the optimal impact of a policy measure.

4.2.4 *What examples of combining modelling approaches can be found in the literature?*

The case study was based on the papers by (Donati et al. 2020), (Kagawa et al. 2015) and (Nakamoto et al. 2015). Interesting other modelling approaches similar to this case-study are found in work of (Litman 2019), (Allwood & Cullen 2015) and (Mount 2016). A general exploration of applying macroeconomic models and resulting impact studies can be found in (de Koning 2018) and (Shancita et al. 2014).

4.3 **Case 3: How can the target of reducing primary raw material input in the construction sector in 2030 by 25% be met**

This case study is a summary of the paper from Cao et al (2019), which estimate the impact of stock dynamics of the building construction sector. Also, it estimates the impact of stock dynamics on economy wide CO2 emissions, capital, and labour use.

Cao et al (2019) developed a soft-linking technique to integrate the dynamic MFA model with the CGE model. An MFA analysis complements the CGE analysis by a more explicit understanding of service provision, in-use stocks, and material cycles in a mass balanced framework. A CGE analysis offers the usual price adjustments over time, influenced by shifting demand and supply and elasticities of productivity factor inputs (labour, capital stock, raw material, energy) and elasticities of demand. This paper used the Chinese building stock as a pilot case to demonstrate the opportunities of such integration. The Chinese building stock refers to the historic built floor areas in China. A couple of scenarios were created to describe the possible future trends of Chinese building stock, depending on saturation level and time.

- Saturation level refers to the average floor area per capita. A low saturation level implies a low floor area per capita.
- Saturation time refers to the time to reach this saturation level: fast (15 years), medium (25 years) or slow (35 years).

In addition, there is reference scenario in which no model coupling occurred, the CGE was ran alone.

Methodology

The following steps were taken to couple the two models

- (1) The **MFA model** was used to simulate newly built floor areas under various scenarios.
- (2) **Results of a regression analysis** allowed to estimate the value added of building construction sector for each scenario.
- (3) This value added served as **input for the CGE model**. The CGE model was run iteratively to find value added that is close to the value added of the dynamic MFA model. For this, in each iteration, the share parameter of investment demand for the building construction sector was changed.
- (4) The **dynamics of the CGE model** make sure that
 - a. Due to the market balancing constraint demands of investors and consumers change. That is, changes in final demand.
 - b. Due to different demand structures from final demand, some businesses benefit from this change (higher output), others do not (lower output). This also changes value added of those industries.
 - c. Substitution of Capital, Labour Energy occurs in CES production function.

4.4 Case 4: How can a better standard for MPG ("Milieu-Prestatie-Gebouwen") stimulate use of wood in construction

In terms of weight and volume, no human activity represents greater stocks of materials than the built environment.

Moreover, the built environment has a significant second-order effect on the location of other capital stock (machines, transport equipment, networks etc.) and the activity of economic activities. Furthermore, many and complicated interlinkages between public and private responsibilities can be observed. Construction therefore represents a significant part of circular economy policy making.

Apart from many non-material policy fields (education, public safety, tourism etc.), several policy topics are relevant in the built environment that have a material component. An integrated modelling of traffic, building requirements, energy use and overall environmental impact is necessary when looking at the interactions and complicating factors in these policy fields. Yet integrated studies like these are scarcely available given the weight of the analytic effort. We expect the IAM to do some of the heavy lifting in analysing interdependent policy targets in this field.

For a modelling approach of this case we will therefore start from the perspective of the Integrated Assessment Model. A combination of Life Cycle Assessment data and MFA techniques will be explored to see if the contribution from LCA and MFA on construction materials can sufficiently meet the demands of the policy research question.

4.4.1 *What outputs are required*

The immediate interest of the CE policy maker will be to bridge the gap between energy efficiency and circular construction. Policy incentives from both fields need to be clarified. It is vital for the CE and energy policy to encourage synergies and avoid counter effective measures such as reducing the footprint of the building materials whilst increasing the energy use during the lifetime of the building.

It is common for a LCA approach to calculate the footprint of both the construction and the use phase of the building. Doing so, both material and energy flows during the lifetime are included next to emissions solely related to the life cycle stages of the building materials.

But the policy question also needs to understand the balance between the inflow of building materials following from the societal demand for buildings and the outflow of material from demolition. This case study describes the attempt to understand the underlying driver for demand for buildings from society, combined with technical/environmental specifics of those buildings. The case study assumes that a considerable shift in material demand can be observed when either a saturation of per capita inflow of buildings is either part or not part of the modelling approach.

A prime example of a required output for CE policy can be found in the target of the construction sector in the Netherlands, to set the amount of recycled material used in annual construction activities in 2030 to 25%. It is important to note that this target relates to a flow. At the same time, the recycled material should contribute to the total amount of materials flowing into the building stock in the Netherlands, even though small amounts of material will be imported from, and exported to, other countries. For this quantified policy goal to be evaluated, we can determine the

required output quite easily. It is necessary to establish what the required production level (volume and type) of buildings should be in 2030 given spatial, economic, and demographic characteristics. Consequently, the result of the modelling exercise should show which main construction materials are in demand for the construction of buildings in 2030 and to match that demand with the supply of recycled material.

4.4.2 *Which shortcomings are experienced if a measure/policy is assessed with a single modelling approach?*

For most available Integrated Assessment Models (IAM) it will not suffice to run the model based on the available data for the built environment. What would be lacking is firstly the types of building, in the IMAGE model (the IAM used in this study) residential floor space demand is part of the dataset. Other types of buildings need to be included. Moreover, information about construction materials per building type are not available in IMAGE, even at a generic level such as concrete, steel etc. In case environmental impacts should be part of the outcome, these impacts could also not be accurately calculated based on the standard IAM database.

The goal of the IMAGE IAM is to make more and more parts of the "Earth system" endogenous to the modelling framework. The strengths and weaknesses of the IAM can be summarized as follows:

Strengths of the combination are land-use and available land surface, biogeochemistry, hydrology, demography, and population health/fitness. General macroeconomic activities are part of the model, as well

Weaknesses of the combination are that sub-models of IAM's usually contain no explicit representation of types of buildings and main construction materials. For instance, emissions related to the built environment can be calculated, but these are determined through emissions factors (EFs, $\text{Emissions} = \text{EF} \times \text{activity}$). As these emission factors are not explicit about the building type and material used, the model is not suitable to evaluate the interventions in the built environment.

In case a Life Cycle Assessment would be applied to estimate the possible demand of construction materials in 203 and the possible share of recycled materials, the analytic shortcomings would be even more obvious. The LCA inventories and databases contain no spatial/geographic information, or any socioeconomic information that would allow to model the stocks and flows on a societal level.

4.4.3 *What other modelling approach do you think you need to implement this measure?*

To model the feasibility of the target to use 25% of recycled building materials annually by 2030, we look at combining an IAM with LCA data. The studies of (Deetman et al. 2020) and (Marinova et al. 2020) serve as the basis of the solution offered by this combination.

Other combinations of modelling approaches could be considered as well. A combination of MFA and an Input-Output Analysis could also be used. However, the representation of demographics and geophysical characteristics such as land area seem to make an IAM a slightly better choice as a starting point for assessing stocks and flows of building materials.

The combination of IAM and LCA information can be visualised as in Figure 6.

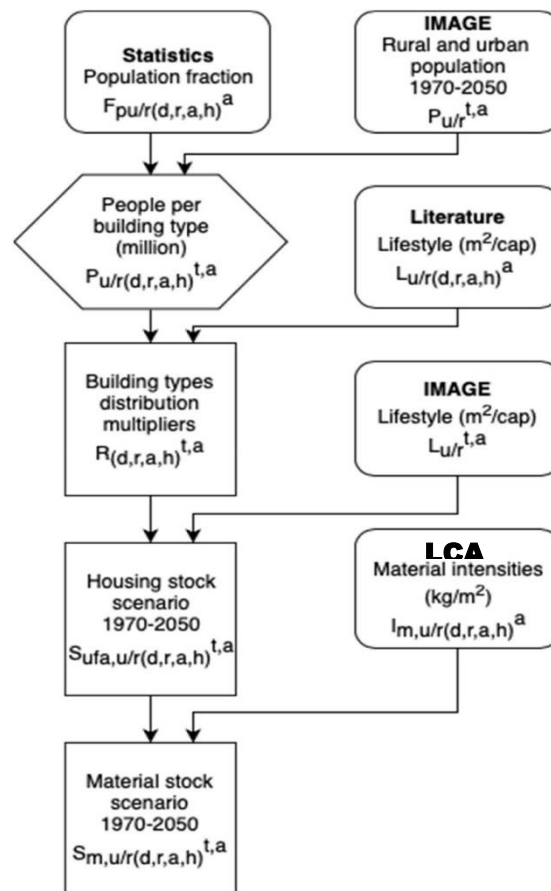


Figure 5: Calculations steps and data sources from Deetman and Marinova studies. A LCA heading is edited for this report to clarify its role

As previously mentioned, the IMAGE model offers residential floor space in m² based on lifestyle. This is denoted by the box centre-right of Figure 6. The additional types of buildings from LCA literature are offices, retail, shops and warehouses, hotels & restaurants, educational buildings, hospitals, governmental buildings, but also buildings for assembly and public transportation. Information about buildings for agriculture and industry is both scant and heterogeneous, so that was decided that they are excluded from the modelling exercise.

The typical material use of buildings in dozens of regions around the world is taken from LCA data. As shown in the published source code⁸, the building materials are described as shown in a sample in Table 12. The values in the table relate to “region 2” (modelled to be the United States) for a detached house in an urban region with a lifetime of 50 years.

Table 12: Excerpt from the (Deetman et al. 2020 database) illustrating the level of detail of materials and some properties of the material being applied to a detached urban building. Showing the material content in kg per m². See table 2 of original document for full detail.

Construction material	Offices	Shops, Retail & Warehouses	Hotels & Restaurants	Hospitals, Educational, Institutional, Transport, Public assembly & Others
Concrete	115	78.5	84.4	101.9
Steel	905.1	700.1	724.2	1029.1
Aluminium	4.8	2.4	4.4	5.8
Copper	3.9	2.3	3.5	3.4
Wood	6.7	11.2	18.5	25.5
Glass	6.5	5.9	3.9	14.5

Based on the modelled lifetime of buildings, the potential for recycled construction material from waste is calculated. The studies conclude that the demand for new construction materials (in) will still strongly outweigh the amount of materials potentially available for recycling (out) in fast developing regions. A crucial aspect that this study highlights are the underlying assumptions of the lifestyle module, that highly influence the types of buildings and the corresponding maintenance aspects during the use-phase that are vital to the application of circular strategies. An important improvement as identified by Deetman is to improve the, still mostly theoretical, potential availability of scrapped building materials to an actual recycling potential. It is advised to look at public statistics to scrutinize the model input with actual data of flows of construction and demolition waste that can be processed into secondary building materials.

Reflecting on the combination of IAM, MFA and LCA, we give the following assessments about on the three recurrent question about applicability.

⁸ [GitHub - SPDeetman/BUMA: A repository for the BUilding MAterials model as described in the Journal of Cleaner Production](#)

Does the combination of models enable impact assessment of a certain quantified target in the future?

Combining an IAM, MFA and LCA allows to assess a quantified target in the future and to model the intertemporal steps towards that future target. This is basically done by taking the demand for buildings as a future target as is done in the Deetman and Marinova studies.

Does the combination of models enable impact assessment of individual policy measures starting in base year?

Given the integrated characteristics of IAM, specific policy interventions are harder to isolate i.e. identify. New work conducted in 2019 and 2020 suggests it is feasible to assess individual or even an aggregated set of policy actions from the UPCE (the action program for the CE transition in the Netherlands).

Does the combination of models enable impact assessment the maximum (using reasonable assumptions) impact of constraint on a certain indicator for instance CO₂ (potential study).

Yes, it is considered a key strength of IAM. The model allows to be forward looking and have predictive characteristics. An IAM allows to explore sensitivities and adjust input settings to general policy interventions and see the range of possible outcomes for the geo-physical environment.

4.4.4 *What examples of combining modelling approaches can be found in literature?*

The combination of an IAM and LCA as described in this case study is based on the following two publications of (Marinova et al. 2020) and (Deetman et al. 2020). A review of strategies to impact GHG emissions by major capital stock such as buildings and transport equipment can be found in (Hertwich et al. 2019). A general introduction of the interdependency between climate policies and resource efficiency can be found in the (IRP 2020) report.

4.5 Case 5: Recycling, what if X% of plastics are either mechanically or chemically recycled?

This last case combines a LCA and MFA modelling approach.

Recycling of plastic waste is commonly divided into four categories (Singh et al. (2017)):

- Primary: mechanical recycling without downgrading
- Secondary: mechanical recycling with downgrading
- Tertiary: chemical recycling typically breaking down polymers into monomers
- Quaternary: disposal either through incineration or landfill

Taking the Netherlands as an example, plastic waste can be split into segments based on their sources. These can be wastes from automotive, construction and demolition, e-waste, household waste, etc. Each source of plastic waste can be characterized based on average polymer composition. This results in high uncertainty in terms of polymer composition in each stream.

The polymer composition of common waste streams, colloquially known as DKR mixes, becomes then the attention point when wishing to process such mixes via

different recycling routes. In terms of quality of the secondary raw material, the recovery process will influence into what part of the manufacturing chain such secondary material may be introduced. In mechanical recycling, pure stream recyclates tend to find their way back into dedicated production processes where the same polymer is being used (where composition matters) or if it is a recyclate mix, into applications where product composition is not an issue. In chemical recycling, several processing routes exist such as thermal cracking, gasification and chemolysis. In such processes, the secondary output is mostly a monomer wherein the previous chemical bonds have been broken by the chemical process. The products of such processes are typically gases or liquids (oils) that can be used in the refining or production of new polymers. A new emerging process of “physical” recycling called dissolution uses heat and solvents to break plastics into their original additives and polymers.

LCA assesses the changes in environmental impacts compared to a reference (current situation). It can assess the effects of the introduction of a specific technologies. It can also assess the effects of a specific quantitative targets, e.g. X% of mixed plastic waste treated pyrolysis. For more general targets, e.g. 50% of plastics recycled, assumptions/research must be added on the technologies to achieve these targets. If these are not accounted for, trade-offs are likely neglected, e.g. it would be assumed that 50% of primary plastics are replaced with aligned environmental benefits, but the impact e.g. arising from energy use would not be considered. An LCA cannot assess policy measures that are directed to innovation or behaviour change, or it would need to learn from other models/disciplines which innovations or behavioural changes it induces.

In principle, the LCA would compare the alternative treatment combination to a status quo for a pre-defined (current) quantity and composition. For policy assessment, results for total and future quantities can be of interest. LCA will not predict changes in these quantities or compositions, but they can be incorporated if available from scenarios or other models. As long as the economy stays the same and changes in emissions etc. are still negligible compared to total global emissions, results of attributional LCA can be scaled up to the required quantities. Likewise, LCA will not predict changes in inter-sector flows resulting from other output of waste treatment processes. Again, estimation of environmental effects resulting from these changes, if translatable in replaced (or more to be produced) products can be included.

Taking LCA as a first modelling approach to address this case might lead to shortcomings since this case pertains to an overall assessment of the flows of plastic waste in The Netherlands and its subsequent recovery routes as opposed to a process-based approach. Such an economy-wide study is usually not the scope of a stand-alone LCA but can be the case of a hybrid LCA where the foreground remains an LCI with the possibility to use an IO system as an expanded background matrix to address the “economy-wide” effect thereby increasing the scope of the LCI. Ideally, a physical system is preferred over a monetary system as argued by Ferrão and Nhambiu (2009) when the scope of the case study is about physical quantities to control for price allocations.

If an IO system is used as the foreground system, the resolution of economic sectors will play a key role as the recycling industry is poorly represented in such

systems (Nakamura and Kondo (2002)). This in turn will affect the quality of the analysis in two ways: (1) how to discern from the two different processing routes? And (2) How to create valuation coefficients for such heterogeneous streams?

The first question relates to sector aggregation in an IO system which can be solved using different disaggregation techniques – provided that data exist to perform such disaggregation. Data such as the Dutch waste accounts are a useful source (Delahaye et al. (2011)). It is also important to use a system such as EXIOBASE that has several extensions to the base IO system.

For the second question, valuation coefficients are needed to relate mass with monetary flows. This can be partially solved using commodity statistics and trade databases – provided that the information is sufficient for the disaggregation.

4.5.1 *What outputs are required*

Taking the scope of the case to be The Netherlands different modelling outputs may be obtained in this case. They can be of an environmental impact nature such as LCA impact categories. Economic such as factor inputs, labour, etc. Finally, if a physical system is modelled, physical flows can also be studied with their variations in stock, consumption, and disposal. A combination of all the above may be obtained when using a hybrid modelling approach.

Hence the required outputs to address this case can be listed as:

- Environmental impact coefficients such as LCA impact categories or environmental extensions in an EEIO system
- Macroeconomic coefficients such as the common factor inputs, labour and others present in an IO system
- An overview of the changes in physical flows in the country

4.5.2 *Which shortcomings are experienced if a measure/policy is assessed with a single modelling approach?*

Two cases have been highlighted above:

1. LCI in the foreground with an IO system in the background. Note that this is essentially already a combined modelling approach as discussed in section 2.7
2. IO system in the foreground with an ancillary background system

For the first case, a very robust system can be built wherein the effects of two different recycling routes can be assessed to the scale of the country. This can be coupled with environmental and economical outputs which provides a clear picture of the outcomes of a certain policy intervention provided that the market for both mechanical and chemical recycling can be accurately modelled. The latter is a hard constraint in the success of such a modelling effort.

In the second case, shortcomings may arise with the difficulty to describe both mechanical and chemical recycling sectors. If this is the case, then it will be challenging to model such a policy intervention in a IO system. Although, different publications have recently showed that it is possible to perform some policy interventions pertaining to circularity in IO systems which will be highlighted in section [Error! Reference source not found.](#) despite they are not focused on a particular recycling route of waste.

Does the combination of models enable impact assessment of a certain quantified target in the future?

To a certain extent yes. For example in Wiebe et al. (2019), an extrapolation of Exiobase was done until 2030. If a modelling approach such as the hybrid LCA would be used dynamic changes of the background system would be needed such as the energy system. Accounting for these inventory changes is quite challenging but some literature is available on this topic specially in the application of prognostic LCA.

Does the combination of models enable impact assessment of individual policy measures starting in base year?

Yes

Does the combination of models enable impact assessment the maximum (using reasonable assumptions) impact of constraint on a certain indicator for instance CO₂ (potential study).

Yes. The first case using the translation of impacts of the LCI and in the second case by using environmental extensions.

4.5.3 *What other modelling approach do you think you need to implement this measure?*

At this moment in TNO-CEE a carbon flow model for The Netherlands is in development. This model in the future will be a dynamic stock model – also referred to as a MFA model – whereby information on the whole plastic material chain will be available. It can be considered a MFA combined with a set of LCA. This model will be implemented using the RECC framework (Pauliuk et al. (2020)). Once it is available, it will be of high relevance for this case study although not binding.

4.6 in **Extra Case 1: CGE model in combination with a technology model: Chemelot combination with a CGE model**

Case description

Chemelot is an industrial park with nearly 150 institutions and companies in the chemical and material industry, located in Limburg, and covers about 1600 football fields. Chemelot has the ambition to develop into the most sustainable and competitive chemical site in western Europe⁹. Within project 'Brightside', a couple of program lines have been set out:

1. Reduction of emissions through electrification
2. Reduction of emissions by reduction of naphtha and gas usage
3. Post-processing emission reduction
4. Securing integral process safety and societal acceptance.
5. Transition scenarios and system integration towards 2030-2050. (Modelling of the chemelot site and its connections to the outside world)

The latter program lines resulted in a technological model for the Chemelot site.

Methodology

⁹ <https://www.chemelot.nl/chemelot-en/organisation>

Figure 6 gives an illustration on the Chemelot inputs and outputs in the current situation and in the desired future situation. This figure also illustrates that Chemelot is not a stand-alone industrial park. It is dependent upon surrounding industries, especially those industries that produce electricity, gas and nafta. The link of Chemelot with the rest of the economy can be made by linking the technical model for Chemelot to a CGE model that represents dynamics in the rest of the economy.

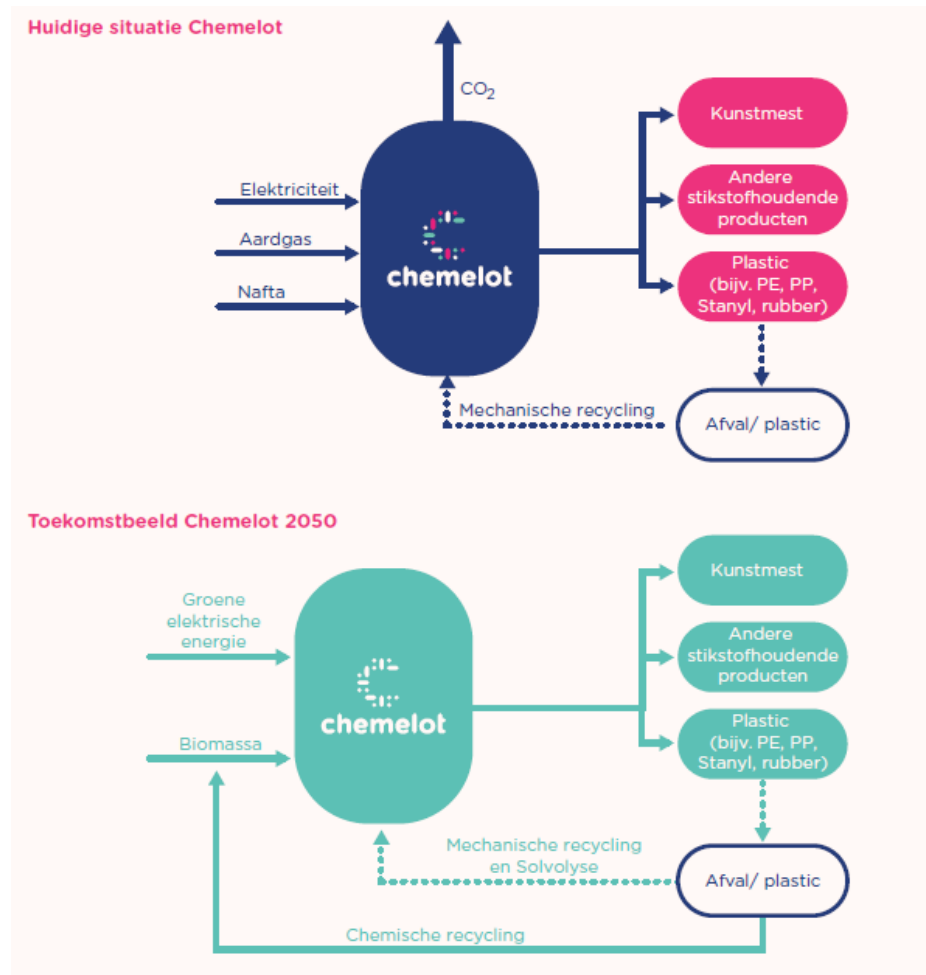


Figure 6: Current and future situation of the Chemelot industrial park, input and outputs.

The linking of the technical model to the CGE could be done in the following manner:

1. The **technical model** for Chemelot is used to predict that amount of Electricity, Gas, Nafta that Chemelot requires from the economy in different scenarios. A baseline scenario describes the situation in 2030-2050 in case of business as usual. This energy demand is input for the CGE model.
2. The **technical model** for Chemelot is also used to predict the stream of plastic products that will be mechanically and chemically recycled.
3. A **CGE model** represents the dynamics in the outside economy. For different scenarios the electricity mix changes between now and 2030-2050. Since Chemelot intends to replace input products nafta and gas by electricity from renewables, it is important that such amounts of electricity are available by the economy in those years. If not, electricity will be provided by grey sources of electricity. This implies that CO2 emissions will occur in different industries in the economy. CO2 emissions that occur in

other industries are not captured in the technical model for Chemelot, however, will be included by the CGE model.

The CGE model can capture the international demand and demand shifts, given the price changes of both electricity and its associated emissions.

4. The **CGE model** provides CO₂ emissions in the rest of the value chain of the Chemelot site. The **technical model** of Chemelot provides the CO₂ emissions on the site of Chemelot. Together gives total “consumption based emissions” related to the flows of products over the Chemelot premises.

4.7 level **Extra Case 2: linking monitoring of waste flows to accounting on a macro**

The need to accurately account for physical flows is salient and self-evident for many circular economy policies.

Relevant environmental impacts can also be evaluated on a macro level, thanks to a link or an extension, to monetary supply and use tables (MSUT). The monetary tables need to be translated in physical units to create the link to environmental impacts. This also lays the foundation for waste flows and footprint/rucksack data to be part of the modelling approach. When the physical SUT (PSUT) is combined with monetary supply and use tables (MSUT) one can end up with hybrid input-output tables (HIOT). This case study presents a brief overview of relevant methodological steps to create balanced PSUT and HIOT data.

The word “balanced” means that no mass/material is left unaccounted for.

The case study describes the process how to integrate heterogeneous data sets to maximize the use of publicly available information that enable new methodological approaches.

This case is therefore a bit off an odd beast, as it will start from the perspective of one modelling approach: Input-Output Analysis. The case will create the path to combining models but will not actually describe any model combinations. The case study will explore what is required to develop the IOA so that it can be linked to other several other models discussed in this study, such as MFA, PE with a focus on energy models or CGE.

Relevant policy questions to this case study come for instance from the manufacturing i.e. metal industry priority or the plastics priority. What if a certain percentage of plastics are either mechanically or chemically recycled, where do these flows “re-appear” in the economy? Which part of recycled metal is subject to recycling and can therefore replace primary extracted metals, given current flows of metals?

4.7.1 *What outputs are required*

Currency is the unit best accounted for in the global economic system. For effective CE policies, the amount of specific raw materials, Joules or other natural units are truly relevant. These data are poorly or not harmonised (accepted) available. Regression analysis or other estimator methods for missing data offer a solution. Policy evaluation requires reliable material flow data with sufficient detail. In case of plastics, a required level of detail could be discerning volumes between the five major types of plastic (HD or LD) PE, PP, PS, PET and PVC. In case of metal, the required level of detail could be to discern dozens of individual metals and the

products they are part of. All these flows should be available as time series over several years.

Examples of data sources that matter, apart from monetary supply and use tables MSUT for the nations/regions that are relevant, are:

- Domestic production volumes such as the Materiaalmonitor from CBS in the Netherlands;
- LCI physical coefficients such as available at www.ecoinvent.org;
- PRODCOM data, for thousands of product groups available for the EU;
- Energy supply and use table, such as EnSUTs (Stadler et al., 2015);
- Balanced trade in monetary units, this means that international trade data from ComEXT/COMTRADE should be consistent for all countries;
- Material extensions that describe the kg per monetary unit;
- Waste flows such as the European Waste Statistics.

For all these sources, policy evaluation would need balanced and consistent Input-Output data over several years. That is offered by the procedures discussed in the next paragraph.

4.7.2 *Which shortcomings are experienced if a measure/policy is assessed with a single modelling approach?*

If monetary supply and use tables (MSUT) are not translated into physical supply and use tables (PSUT), several opportunities for analysis are left untapped. Moreover, it is highly likely that MSUT and monetary trade flows contain several violations of logic and natural science. Flows that are not balanced, do not apply laws of thermodynamics (“you can’t create or destroy mass”). Lastly, practical reasons make that PSUT and other elements of a Hybrid Input-Output (HIOT) table should not be calculated as part of the modelling exercise. Excessive computing power will be needed if physical calculations or other extensions are not part of the dataset. In the scenario that extensions are not part of the exogenous dataset, these extensions need to be calculated endogenous inside the model, requiring the large processing capacity.

On the way to make a PSUT from a MSUT, several challenges need to be met. Problems relating to data shortage are part of the process, so that data gaps can be filled methodologically. Another important balance check that is introduced by the physical layer is that it is ensured that productions receive enough of specified feedstock materials to produce the product outputs.

This type of feedstock balance check is not present in monetary SUTs since there is no distinction between distinct types of inputs.

An overview of steps in the (copied in its entirety from Schmidt & Merciai 2017) show the steps that create a PSUT from an MSUT. The recent PANORAMA project aims to take step 3, 4 and 5 in an integrated way, improving the robustness of the outcomes.

Table 13 Steps in Physical SUT

Step	Description
1. Revision, gap-filling and formatting of physical production data.	Data collection has two main limitations. From one side, it does not cover all the required flows; hence, some values need to be estimated. On the other side, collected data can be inexact and a

	revision is required. Finally data need to be rearranged to fit within a supply and use framework
2. Calculation of technical and distributive coefficients	Many productions convert raw materials into processed products and technical coefficients play a key role. Some technical coefficients are obtained from collected data, other from literature and, finally, from the monetary level of Exiobase 3.
3. Determination of national product minimum availability	Within each country, certain raw material product requirements are necessary to implement specific level of production/consumption. Otherwise, the risk is to determine a lack of raw materials/consumption goods that can imply an irrational distortion in the use/supply side, such as an enormous variation of change of inventories. This step relies on the calculation of technical coefficients.
4. Trade linking and inevitable revision of data	Once the first three steps are determined, it is necessary to specify the bilateral trade between different economies to assure that minimum required products are available in each market.
5. Mass balance within economies and extensions	The final

The mathematical representation of these steps are given in the referenced literature. Some additional checks enable further sophistication of the resulting PSUT. We describe here checks on technology, productivity, waste, and price conversion.

It is essential that the data used adheres to physical realities relating to material and realistic assumptions related to labour, capital, or resource productivity. Datasets in the shape of PSUTs/HSUTs can only be built considering engineering information, properties of materials, conservation laws. All this information, which can be defined as physical constraints, is relevant for the construction of a consistent physical database. Therefore, for example, whenever a simulation implies a change of productivity, or a change in the productive function of activities, or modifies the properties of materials, it should be important to consider these constraints. Examples of constraints can be mass or energy balance or the fact that a day has 24 hours.

Technology and learning curve assumptions are meant here as well. Using a rectangular choice-of-technology (RCOT). RCOT is an optimization model built upon a SUT. Checks to make sure the economy is producing waste at a rate consistent with statistics. In (Nakamura & Kondo 2002) the flows were introduced on a global level (WIOM), thereby initiating the modelling of waste in the IO.

Lastly, there is the issue of prices to be considered. PSUTs may disclose different properties of products, so, given the chosen aggregation, heterogeneous (matrix of) prices are needed to move from MSUTs to PSUTs. Therefore, attaching physical extensions to MSUTs does not assure that, when implementing a shock, PE and CGE respect physical laws used to build the PSUTs. Therefore, it is suggested to use a PE or CGE model based on price multiplied with quantity. In this case a consistent physical reality may coexist in parallel with economic modelling, but a simple price and quantity based model without additional checks can be acceptable, as long as the shortcomings of having no physical checks in place are discussed in the work.

4.7.3 *What other modelling approach do you think you need to implement this measure?*

The fact that monetary supply use tables can be used to construct balanced and realistic physical tables featuring mass (see previous section), energy and or time availability of capital stock is obviously a great asset to assessment of circular economy strategies. This opens the door to other modelling approaches that allow for physical Input Output Analysis to be used in unison. Having proper physical extensions to an Input-output dataset, the opportunity is created to use the physical extensions in MFA, PE and CGE. The obvious first useful combination would be with a waste Material Flow Accounting. Another combination would be with a Partial Equilibrium model that is tailored to analyses an energy system. The explicit and balanced energy quantities in a HIOT can be of great value to that PE. Another combination could be made with a MFA application. The framework physical supply and use tables (PSUTs) are compatible to the defined Systems of Economic and Environmental Accounts (SEEA) (Hoekstra et al. 2015) such as shown in Table 14.

Table 14 Environmental and physical asset structure of the SEEA (Hoekstra et al. 2015).

		Produced assets	Environmental assets
Additions to stock	Growth in stock	Gross capital	Extracted natural resources
	Discoveries of new stock		
	Upward reappraisals		
	Reclassifications		
Reductions of stock	Extractions	Waste	Residuals flowing into the environment
	Normal loss of stock		
	Catastrophic losses		
	Downward reappraisals		
	Reclassifications		

It is a technical reality that recycled materials differ from their virgin counterparts. This is an argument to use LCA techniques and/or LCI data to improve the accuracy of the PSUT.

5 Discussion and recommendations

5.1 Discussion

In this section, we present initial conclusions, followed by a discussion about the key question laid out in the introduction of this report: how to characterise and combine a range of quantitative modelling approaches, in order to be able to support policy makers in addressing CE policy issues.

A few, fundamental, conclusions can be drawn with relative ease:

- Policy targets can be translated in quantified CE research goals. Those research goals can be tackled more effectively using combinations of the modelling approaches that are discussed.
- Economic effects are explicit only in the IOA or CGE approach, but it is the awareness that some external economic effects need to be incorporated into the modelling approach that justifies combination with all other modelling approaches that are discussed.
- There is a ongoing interpretation issue between results based on monetary value and quantity, and actual physical data that has been amended by additional checks for technology adaptation, waste generation and mass balance.
- The case-studies show enough potential to reach the requirements for embedding modelling approaches and research questions into an effective policy making process such as discussed in section 3.1. The most demanding effort seems to engage policy makers and modelling makers in a cooperative process. This will require close communication and exchange of expectations from both policy maker and modeller.
- Existing published studies offer a good starting point for investigating the merits of combining modelling approaches, yet the number of useful studies is small (<10) in all cases that were researched in this study.

On combining modelling approaches, we conclude:

- If we want to include detailed LCA like information in an economy wide approach, e.g. IOA or CGE, the mathematical methodologies are well established, but the knowledge of a sector composition to a level where it approaches the product detail is not available publicly. Such an inclusion could be useful to model economy wide effect of introducing new more circular technologies. This gap might be filled step by step for the Netherlands, starting with sectors relevant for specific circular economy questions.
- It is a common feature of many of the considered approaches that they are suitable for estimating the effects of certain changes in the economy/the considered system but are less suitable for estimating how these changes can be brought about (except for financial measures). More social science-based approaches, like Agent based Modelling, should be explored in this context.
- The extra case-study (§4.6) offers a no-regret option for any macro-economic modelling approach, as it proposes generic activities that result in output that can serve as input for many other studies.
- The improvement of the data integrity between monetary data and physical material flows needs to be enforced in any case. Before an output of a combination of approaches is investigated, it is important to establish a

robust understanding of the output of the individual modelling approaches. Results of an individual approach can be obtained at the start of a possible combined application by looking at literature for published comparable studies. Looking at individual results before the start of a combined application self-evidently requires knowledge and experience from the project team: it is not feasible to conduct a combination without having expertise of all the individual modelling approaches “in house”. For example, for LCA, it would be false to assume that an impact (reduction) found for a specific technology for a specific product (e.g. pyrolysis for a specific plastic waste stream composition) could be reached for all products (e.g. all plastic waste) and under all circumstances (e.g. under a changed energy market).

A few practical conclusions, that are nevertheless vital for a successful follow-up of this study, can be drawn:

- It is hard to provide an upfront estimate of the required effort and time to finalise an application that features combinations of models;
- Data availability is key, an aspect that is paradoxically often overlooked.

A tempting question to ask is which modelling combination(s) are worth most attention in the follow-up of this study. For this, we need to discuss the additional analytical power obtained from combining modelling approaches. The combinations of models as discussed in chapter 4 offer a new perspective on the overview table of modelling output introduced in chapter 2. See Table 15.

Table 15 Overview of combination of approaches from chapter 4

[illegible]

It shows that all combinations increase the coverage of relevant modelling aspects. Especially the combinations 1, 2, 4, and 5 feature a **detailed product and sector level environmental impacts**. Combinations 2, 4, 5 and the extra case 2 demonstrate the ability to accurately model **stocks** in a novel addition to the approaches that are based on national statistics and monetary information, such as CGE, PE and IOA. The need for dynamic analysis (market uptake of new products) are also present in combinations 3, 4 and the extra case 1.

The **key** in modelling CE policies is that models or combinations of models should be **able to combine the three following elements**: 1) accommodating high level of detail available in bottom up LCA/MFA models, 2) insights in product stocks and vintages and the outflow of obsolete products that can be subject to CE improvements as provided by dynamic MFA models, and 3) the dynamic aspects related to for instance price elasticities and product/technology substitution elasticities as present in dynamic models. IAM's such as IMAGE and CGE's such as EXIOMOD should deliver insight in the dynamic aspects of circular changes. Partial equilibrium models by nature do not cover the full economy.

If we want to include detailed LCA or MFA like stock-flow information in an economy wide approach, e.g. IOA or CGE, the mathematical methodologies in general are well established. Most of such detailed LCA or MFA information is however not structurally available or if it is, such as the micro-data of CBS, not available publicly. This gap might be filled step by step for the Netherlands, starting with sectors relevant for specific circular economy questions or using generic databases (such as the life cycle inventory database Ecoinvent) as a stopgap. Another problem is that a full integration of high product detail in dynamic models (IAMs or CGEs) will make the overall model too heavy to make good model runs in a reasonable time span. In practice, currently even in studies with detailed CGEs with 160 sectors and 48 countries like EXIOMOD usually sectors and countries outside the study focus are aggregated to ensure a reasonable model run time.

The **most promising route** uses hence a (dynamic) MFA approach to analyse product stocks and particularly end of life flows. LCA then can be used to analyse **in detail the improvement options**, scaled up to national volumes of product use. Such information can be soft-linked to a dynamic model, to get insight in how changes work out dynamically in the wider economy (e.g. by aggregating detailed information on a few products to a specific product category in a CGE, or to add a **specific product category** in the input-output database underlying a CGE). Note that the combination of LCA, MFA and CGE was not part of any case study.

A point of discussion would be if the legacy of IMAGE 3.0 and EXIOMOD offer ample base to make these two models the basis of further research. It seems clear that in terms of data, reputability, and availability, these two models offer a superior prospect for IAM and CGE respectively, compared to a PE, (p)IOA or MFA model made from scratch. At this point in time, IAM (IMAGE) and CGE (EXIOMOD) seem to offer a better starting point for quantitative CE policy modelling than the energy system models.

They allow to combine the three vital criteria for a macroeconomic model: accommodating high levels of detail from bottom-up models, the accumulation of stocks and assessment of dynamic aspects related to for instance price and

technology. This is supported by the in-depth discussion in this study of existing combinations of modelling approaches.

It should be noted that the preference for CGE, augmented by IAM, MFA and LCA, represent the danger of “what you see is all there is” bias. Given the fact that behavioural economics models are left out of the scope of this study, there is a danger that the merits of behavioural models such as Agent-Based Modelling will be left unused. It should be a recommendation to keep considering further incorporation of behavioural models in future work. Alternatively, these behavioural modelling approaches can be run separately and be compared with the approaches in this report in a post-processing review.

This study aspired to look at how physical models from the energy world are set up (e.g. TIMES, POLES, PRIMES), and what can be learned from this for modelling circular material flows. The case-studies offered insufficient ground to investigate the advantages of these partial equilibrium models, as discussed in § 2.4. Therefore, no conclusions can be drawn about the use of the methodology that is used in energy system models (TIMES, PRIMES and POLES) in the context of a circular economy.

Another point of discussion is what is needed to follow-up on the intention that was expressed in the MSCE (“Monitoring en Sturing Circulaire Economie”) to include a significant contribution from quantitative modelling work in the next Integral Circular Economy Report which is due 2022. See the textbox for further insights.

Textbox: What is required to construct a baseline in 2023 for macro-economic CE models?

An ambition could be to develop a macro-economic baseline scenario answering the question “what are the expected impacts of policy measures suggested in the CE transition agendas on economy and environment?” For this, a baseline scenario is both a logical and essential first step.

To highlight the major changes required between now and 2030/ 2040, the baseline scenario should be placed next to a business-as-usual situation (BAU scenario). The BAU-scenario includes extrapolation of current trends. Current trends do not bring us fast enough towards the Circular Economy. For example, MSCE research suggests that even though resource efficiency improves, total material use still increases. Also, it explains that the Dutch economy is still more or less linear, aside of the recycling and repair activities. The number of businesses that implemented circularity principles increased less fast than the increase in total number of businesses. Still, there are some pilots and initiatives that gained experience in more advanced circular business models like circular product design, producer responsibility, sharing-platforms. These are the exceptions that confirm the rule of the rest of the economy.

The baseline-scenario should explain what the economy looks like when the ‘ways to accelerate the CE-transition’, as described in policy documents, have been implemented. Some examples for recommendations made for policy makers are (1) phasing out products with a short life-time via a ban (2) removing barriers to enable the creation of service-as-a-product initiatives (3) investing in

technologies that enable high-quality recycling (4) environmental costs should be reflected in prices of raw materials. These are just examples. It is recommended that the government starts quickly with implementing the necessary changes.

What is needed to create such a baseline scenario?

To develop a future pathway that represents the baseline-scenario, it should be clear what is included in the scenario following the goals in the five CE transition agendas. These goals have continued to be discussed throughout 2021 and are expected to be published early 2022. It should also be clear what is already part of the BAU-scenario. *Therefore, a qualitative story path should be developed between now and 2030/ 2040 for both scenario's.*

For the BAU-scenario, it should be decided which current trends should be included in the BAU-scenario and which not. Think about growth in GDP, Population, Resource Productivity levels, recycling rates, repair rates, use of single-use products and more.

For each development or policy intervention, a quantification is needed. Think about: What year is the policy intervention implemented? When to expect the first effects of the policy intervention? What are the (quantified) targets that should be met in a future year? In case of taxation of products, what will be height of the tax increase? In case of developments due to for example changes in consumer behaviour, assumptions must be made on the adoption pace of the circular product compared to the conventional product. It is obvious that a qualitative story cannot be input to a quantitative model.

In addition, there is a need for sufficient data on circular initiatives. Examples of what we mean with good data is:

- Input-Output and Supply and Use tables that include **trustworthy** data on the production structure of recycled products. This cannot be one aggregated sector for all products. For example, recycling of steel and plastic look nothing alike.
- Updated Inventory databases for LCA analysis that include the necessary (innovative) materials and products to be implemented in the ICER-scenario.
- **Timeseries** on important CE-indicators, or indicators that are related. Think about prices of raw materials versus secondary materials, recycling rates, repair rates, share of businesses that produce products via a circular business strategy (e.g. producer responsibility, circular product design, reparability of a product). The list of time-series needed should be created once it is clear what should be part of the story paths, and how to quantify.
- In case an implemented measure for 2025 or 2030 is currently in a **low TRL-phase, solid assumptions** should be made on the future production structure, costs and demand of the innovative product.

5.2 Recommendations as reflected in a NWA-ORC project

The way forward from the learnings of this project seems to converge in the recent NWA-ORC 2020/21 project. The ideas that are in the project proposal can as such be considered as a focused set of recommendations that emerge from the discussion of the results of this report.

The NWA-ORC project will consist of 3 work packages. The first and third work package are to respectively deal with 1) implementing circular designs and business models with companies, 2) designing and applying an appropriate modelling framework for assessing environmental, economic, and social implications of a circular economy transition, and 3) assessing and suggesting mitigating measures for undesired distributional effects, such as power and value-added concentration.

The relations between work packages are indicated in the figure below.

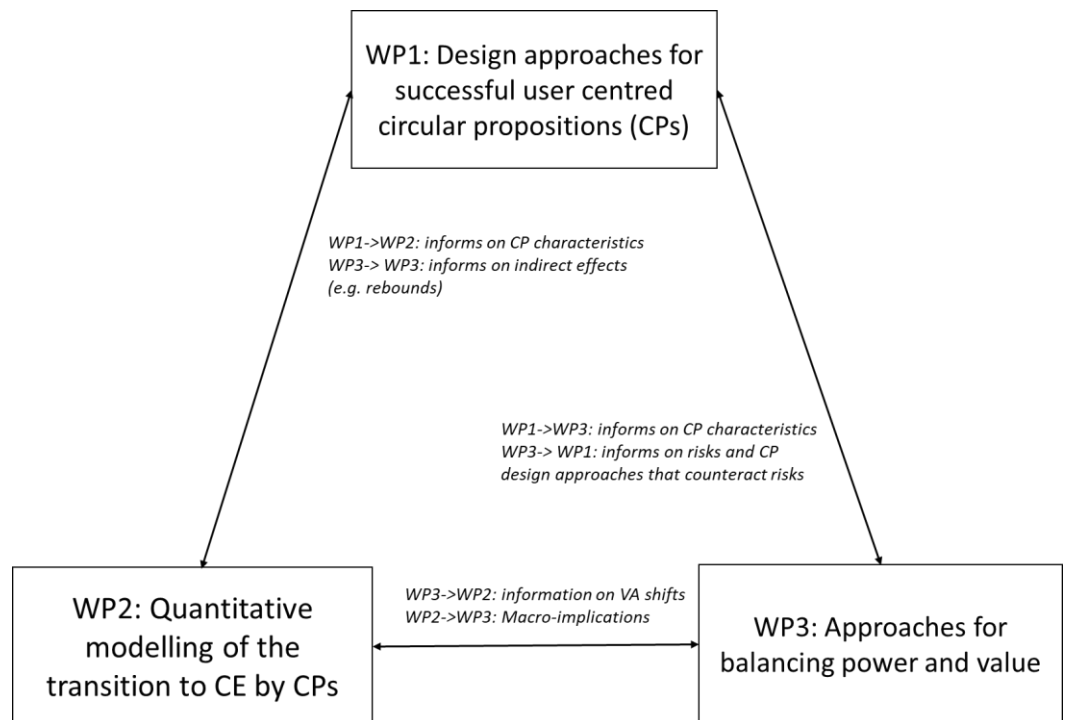


Figure 7 WP structure of NWA-ORC proposal

Work package 2 of the NWA-ORC 2020/21 project (see Figure 7) the one that will build on insights that are discussed in this report. The activities in this work package 2 represent therefore the best possible recommendations about the way forward in quantitative circular economy modelling.

Firstly, the concept of the other two work packages are discussed. This is done because concepts in these work packages can compensate for the dearth of discussion of behavioural models in this report.

The goal of WP1 is to contribute to the transition towards a circular economy by exploring best practices and how the introduction and scale up of Products-as-a-Service (PaaS) and other circular business models (e.g. subscription models, buy-

back models, extended service agreements, sharing platforms), all with a focus on closing loops, can stimulate more sustainable end-user behaviour. The goal of WP3 is to shed light on the social impact of a circular sustainability transition, which is far from clear, raising justice and /fairness concerns. Prominent business models associated with the circular economy – such as product service and platform business models – may lead to (desired) sustainable asset use, but simultaneously increase power concentration and value/profit generation among platforms and asset owners at the detriment of households and employees. In parallel with WP2, WP3 will identify and analyse specific business models and sectors where such negative social impacts may occur and identify strategies that can mitigate them, both from a bottom-up and a top-down perspective. Bottom-up strategies will rely on the actions of actors in the value chain (e.g. ensuring that new circular business models implement a revenue sharing model that distributes value captured fairly; or setting up collaborative organisations of smaller actors in value chains that can create counterweights to actors that occupy power nodes in value networks). Top-down strategies will address regulatory and policy conditions, requiring adjustments in institutional settings for which government intervention is often key.

As said, the discussion of the results of this report are linked to the second work package, and less so to the first or third work package. The overall goal of work package 2 is to provide a modelling suite that can assess the implications of a transition to a circular economy in terms of economic value and wealth creation, distributive effects, and environmental impacts.

To build these, we need information from life-cycle libraries, the (static) environmental/economic implications of implementing circular business models, and information on stock-related waste output.

As discussed in this report, traditional CGE models are calibrated on historical trends, but historic observations do not cover sufficient data to extrapolate towards a future economy systematically different from the past. The newly anticipated model will describe both economy value (euros) and material flows (kilograms). Currently, such hybrid models only exist where one model is a satellite of the other. A consistent integration will be an original contribution to science, as follows from the discussion in 5.1.

For this purpose, this work package 2 aims to develop new data (life cycle assessment, stock-flow MFA information, and potential diffusion levels of circular business models), a new type of integrated macroeconomics-material model, and to provide tools for quantitative assessment of policies aimed at circularity. The new tools developed in this way will help policy makers to identify effective policies that bring circularity while protecting income and employment. The groundwork, that is the systematic library of life-cycle assessments, the assessment of societal stocks of products, and the amount flowing to waste in relation to diffusion of new circular business models, will also contribute to science, enabling other researchers also to draw information and data from this project.

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