



Combinations of material flow analysis and life cycle assessment and their applicability to assess circular economy requirements in EU product regulations. A systematic literature review

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ABSTRACT

We conducted a systematic literature review of 44 prospective studies that apply the combination of material flow analysis and life cycle assessment. Our study investigates the characteristics of existing combinations and their applicability to policy impact assessments using the example of the EU Ecodesign Directive.

Along with the increasing number of such publications in recent years, there is great variation in the type of modelling, spatial and temporal scope, study area and additional characteristics. Studies range from sequential analysis to integrated one-software modelling, and from considering only dynamic material flows to utilising dynamic life cycle inventory data. Most studies conduct country-scale analysis and the combination is applied across economic sectors. Combining material flow analysis and life cycle assessment approaches has high potential for assessing the long-term environmental implications of circular economy policy measures. Our review revealed a diverse landscape of existing studies and highlighted the integrated modelling of material flow analysis and life cycle assessment as a holistic and flexible approach with suitable characteristics for assessing circular economy measures under the ecodesign framework.

1. Introduction

In its Green Deal, the European Commission set itself the overarching goal of reaching carbon neutrality by 2050 and decoupling economic growth from resource consumption (European Commission, 2020), a goal where the transition to a circular economy (CE) is expected to play a crucial role (European Commission, 2020). Increasing consumption is responsible for many environmental problems, and one of the ways to reduce the high environmental impacts associated with products (Sala et al., 2019) is through stringent policy. For energy-related products, the EU Ecodesign Directive offers a framework for setting ecodesign requirements, and CE-related requirements have increased in recent years (Barkhausen et al., 2022). Different approaches to assess future product policy impacts exist, including material flow analysis (MFA) and life cycle assessment (LCA). Both are independent methodologies, but with clear overlaps. While LCA inherently includes an assessment of the

material flows during the life cycle inventory, the presented literature review focuses on studies going beyond this classical practice. When combined, these two methodologies are assumed to be suitable for evaluating the long-term environmental impacts of CE policies (Elia et al., 2017; Merli et al., 2018; Anandh et al., 2021), but a concise overview of how they are combined is to-date missing.

The following subchapters provide further information on MFA and LCA (1.1), an overview of MFA and LCA usage in EU policy and specifically in the Ecodesign Directive context (1.2), and more information about the motivation, objective and contribution of our systematic literature review (1.3).

1.1. Material flow analysis and life cycle assessment

In response to the need for extensive evidence-based quantitative information regarding the use structure, losses and circularity of

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material systems (Graedel, 2019), MFA has been developed as a methodology for quantifying the stocks and flows of materials within a specified system. Systems are defined by spatial and temporal boundaries and by the type of material, which ranges from single substances to complex physical goods. The main principle of MFA is the conservation of mass, which makes it possible to apply mass balance to any process and stock of the system by accounting for inflows and imports with outflows and exports (Brunner and Rechberger, 2017).

In static MFAs, the mass balance is performed within one time increment, while dynamic MFAs track changes over multiple time intervals. MFA models can be stock-driven, where stocks and their material composition are exogenous input parameters while inflows are calculated endogenously, or inflow-driven, where it is the other way round (Wiedenhofer et al., 2019). In both cases, the mass balance enables the analysis of stocks and flows of special interest but unknown quantities due to inaccessible or not practicable physical accounting. There is no international norm or official standardisation for MFA, but there are some national norms, such as a norm for MFA in Austria (ASI Austrian Standards International, 2005). The absence of a standardised MFA procedure has the advantage of high flexibility in each case-specific application, but it can impede the comparability and interpretation of results. Therefore, extensive documentation of each methodological procedure is indispensable for any MFA study to achieve transparency and reproducibility. Brunner and Rechberger (2017) proposed a generic standard iterative procedure for MFA with four steps: Problem definition, system definition (determination of system boundaries and relevant materials and processes), determination of material flows and stocks (collection of input data, balancing of materials, consistency checks and uncertainty evaluation), and illustration and interpretation of results.

MFA studies have a wide variety of goals and objectives, ranging from the micro to the macro level. The spatial scope comprises single processes, companies or cities as well as regions, countries or even the whole globe. The period of time can cover historical and recent flows in retrospective studies or future flows in prospective analyses combining MFA with scenario analysis (Baars et al., 2022).

MFA simulations can be conducted in universal environments like programming languages (e.g. Python, R), system dynamics software (e.g. Vensim) or spreadsheet programs (e.g. Excel). In addition to these universal environments, there are also MFA-specific frameworks such as STAN (Technische Universität Wien, 2012) or ODYM (Pauliuk and Heeren, 2020). Exogenous variables such as data and additional assumptions serve as the input for any MFA model. Common data sources include statistics or surveys from governmental agencies (e.g. geological surveys), intergovernmental organisations (e.g. UN), industry associations and private companies or consultancies (c.f. (Cullen et al., 2012; Rostek et al., 2022; Bertram et al., 2017)). Uncertainties embedded in exogenous parameters and methodology are unavoidable and it is essential to examine these using uncertainty evaluation and sensitivity analysis as an integral step within MFA.

Since the early 1990s, MFA has been applied in various domains at regional, country and global levels. Socio-economic metabolism and metal cycles comprise an early and ongoing objective for MFA studies (Graedel, 2019), while additional studies on construction minerals and specific products have emerged more recently (Baars et al., 2022). MFA has become an established methodology in resource management, environmental management, and waste management (Brunner and Rechberger, 2017), and monitoring and simulating the CE has become an additional important field of application for MFA (Jacobi et al., 2018; Gao et al., 2020).

With regards to environmental impact assessment, the forerunner of LCA can be dated back to the 1970s when different methods were used (Klöppfer, 2014). After decades of development, LCA has now become a standardised methodology under ISO 14040/44 (ISO 14040:2006, 2006; ISO 14044:2006, 2006) to assess the environmental impact associated with a product or service by addressing the entire life cycle

from raw material extraction to end-of-life management. An LCA study comprises four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation, and is performed in an iterative manner to optimise processes, identify hotspots and trade-offs in various environmental aspects, and support decision making. The inventory phase analyses the input and output data of the system, which includes the material flows and therein follows the approach of an MFA. Open source and commercial LCA databases are available, providing transparent high-value data sets of regional and international industrial activities, and LCA specific software was developed with a broad range of functions, such as uncertainty analysis.

Besides ISO standards, several deliverables and guidelines have been published to assist practitioners in conducting consistent LCAs. However, the ambiguity in terminology and definitions has been causing methodological inconsistency (Schrijvers et al., 2016; Köhler and Pizzol, 2019; Plevin et al., 2014; Zeller et al., 2020; Finkbeiner, 2021; Heijungs et al., 2021; Suh and Yang, 2014).

In LCA, a case-specific system boundary needs to be defined based on a set of criteria (ISO 14040:2006, 2006; ISO 14044:2006, 2006) and for many aspects, such as spatial and temporal (Tillman et al., 1994). The geographical boundary not only represents the production site and supply chain, but also indicates the sensitivity of the local receiving environment (Tillman et al., 1994). The temporal boundary of a study can be differentiated into many types: In their review, Lueddeckens et al. (2020) identified three time horizons (one defined in goal and scope, one for the inventory, and one for the impact assessment). When considering the time horizon in life cycle inventory, time-dependent or dynamic LCA can then be understood as integrating parameters such as supply delay to achieve higher granularity of the system over time, either over short-term technology optimisations or long-term operational and environmental changes (Tirutu-Barna et al., 2016).

Specific LCA approaches are applied for particular purposes. For example, when assessing the futuristic state of emerging technologies, prospective LCA, a synonym for anticipatory (Wender et al., 2014) or ex-ante LCA (Cucurachi et al., 2018) is applied with adaptations in the methodological choices to reflect the research goal (Arvidsson et al., 2018).

LCA methodology and life cycle thinking are also applied to policy design and implementation. Despite criticism (Finkbeiner, 2014; Pedersen and Remmen, 2022), the product environmental footprint (PEF), as a harmonized methodology of LCA, was developed under the initiative of The Single Market for Green Products (European Commission, 2012).

In addition to the information provided above, a table summarising the characteristics of MFA and LCA can be found in the supplementary information A.

An example of the use of life cycle thinking and material flow based approaches in policy is the development of product regulations under the EU Ecodesign Directive, which is discussed in more detail in the following section.

1.2. Application of material flow analysis and life cycle assessment to evaluating circular economy requirements using the example of the EU Ecodesign Directive

The EU Ecodesign Directive (Directive, 2009/125/EC and prior Directive, 2005/32/EC) aims to enhance the environmental performance of energy-using and energy-related products by imposing eco-design requirements, including informational and performance requirements on energy efficiency. Via specifying these measures in so-called implementing measures, EU regulates products sold in the EU market (Barkhausen et al., 2022). Prior to establishing these requirements, the potential environmental impact of the requirements shall be evaluated.

Within the context of the Ecodesign Directive, there is a structured approach to analyse the environmental improvement potentials (policy

impact assessment) of product groups using the Methodology for Eco-design of Energy-related Products (MEErP) (Kemna et al., 2011). Currently, at its core, the MEErP comprises a techno-economic-environmental assessment that evaluates life cycle costs and the environmental impacts of representative products and design options. The EcoReport tool has been developed for the environmental impact assessment. This is a public Excel-based tool containing a database of unit impact indicators for close to 100 materials and processes, to statically evaluate selected and weighted environmental impact categories based mainly on the bill-of-materials of the final product.

In the scenario analysis phase of the MEErP, the impacts of product design options on the market are assessed using a basic stock model approach (including annual sales, stocks, and average unitary impacts of the most significant environmental impacts). Furthermore, the MEErP proposes to consider changes for the global warming impact of the electricity mix when conducting the scenario analysis (Kemna et al., 2011).

In the past, impact assessments under the Ecodesign Directive framework focused mostly on energy consumption during the use phase as the most important environmental impact category and placed less emphasis on aspects of material efficiency (Bundgaard et al., 2017), but especially since 2019 there has been a marked increase in the number of CE related measures (Barkhausen et al., 2022). Furthermore, the EU recently published its proposal for Ecodesign for Sustainable Products Regulation, which will expand the scope of products beyond energy-related one's (European Commission, 2022). As the MEErP mainly uses a static environmental assessment focusing on the environmental impacts of material and energy consumption in the use phase, it may come to its limits with the new product groups and when assessing the long-term implications of CE policies on a wide range of environmental impact categories. To address these shortcomings, the MEErP is currently undergoing a revision process to ensure that it is still fit for its purpose. Within this revision the systematic inclusion of material efficiency aspects in the modelling is one of the central goals (European Commission, 2021).

According to the current draft of the updated version, there will be the possibility to use dynamic stock models with lifetime distribution functions (allowing to e.g. consider improvements in product durability). The EcoReport tool is expected to be aligned to the impact categories of the Product Environmental Footprint (PEF), and the modelling of product end-of-life phases (e.g. recyclability or recycled content) will adopt the allocation methods of the Circular Footprint Formula (CFF), where the environmental burdens and credits of end-of-life operation are allocated between supplier and user of recycled material (Gama Caldas et al., 2021).

The proposed changes to the MEErP and the EcoReport tool would improve the inclusion of CE aspects when assessing the products in the preparatory studies, but it remains to be seen how well the new approach will allow dynamic analyses and how well it is suited to modelling the impacts of CE measures on a system level (going beyond simply comparing product variations). The current approach under the MEErP can be described as a simplified LCA that is coupled with a stock modelling approach to assess the environmental benefits of a market roll-out of single product improvements, following the premise of practicality to offer a widely applicable approach with sufficient but not excessive level of detail. By analysing the existing combinations of MFA and LCA, we want to assess whether there is an alternative or complementary approach for modelling CE aspects in product policy impact assessments using the example of the Ecodesign Directive.

1.3. Motivation, objective and contribution

As shown in section 1.1, MFA and LCA have distinct characteristics. LCA shows a high potential to assess the environmental performance of CE strategies, but is mainly applied at product level (even though results

can be scaled up to system level) (Corona et al., 2019). In contrast, MFA is well suited for macro scale system analysis with different scenarios over long periods of time, but does not account for the related environmental impact (Corona et al., 2019; Elia et al., 2017). It is therefore of scientific interest to examine the possibilities of combining the two approaches, although this is not a trivial task. MFA is a method with a non-standardised procedure, while LCA is conceptually more defined through the ISO 14040 and ISO 14044, but has many different adaptations and interpretations (e.g. EU product environmental footprint) (EC-JRC, 2010).

Several review studies have pinpointed the potential and need for further research on combining MFA and LCA (Withanage and Habib, 2021; Islam and Huda, 2019; Sakai et al., 2017; Perminova et al., 2016). Baars et al. published a semi-structured literature review (using citation searching) of 33 studies on improving prospective MFA as a decision support tool by combining it with other methods including LCA as a so-called "integrated MFA" (Baars et al., 2022). Due to the large number of assessed methods, the review has a wide scope, and does not go into detail for each method combination. Therefore, it is of interest to extend their research, zoom in, and conduct an entire literature review on the combination of MFA and LCA and its applicability to the CE policy evaluation based on the example of the EU Ecodesign Directive impact assessment. To the best of our knowledge, no previous study has systematically and exclusively examined this combination. This paper reviews the research that has been conducted on the combination of MFA and LCA with two main objectives: First, to examine and characterise the existing types of combinations of MFA and LCA, and second, to identify how different forms of combination can be applied to the CE policy-making process and specifically to the impact assessment of the EU Ecodesign Directive. In doing so, we contribute to research by providing an overview of the characteristics and a systematisation of methodological variations when combining MFA and LCA in future-oriented studies. We also add value for practitioners by assessing how this combination can support decision making.

2. Method

A systematic literature review was performed following the procedure proposed in the PRISMA statement that promotes higher transparency and completeness in review studies (Page et al., 2021). The search query was conducted on July 7th 2022 in the scientific databases Scopus and Web of Science, searching for publications that include the term "life cycle assessment" or "life cycle analysis" and "material flow analysis" or "substance flow analysis" (or the abbreviations "MFA" and "LCA") in either title, abstract or keywords. The search query was deliberately open and did not include a sector or field of application in order to obtain a large number of results and only then to assess the applicability of the method to certain sectors or applications. Only peer-reviewed articles (excluding reviews, conference papers, book chapters etc.) were included; no limit was set on the year of publication. After identifying this initial set of records, the bibliographic information was extracted from Scopus and Web of Science, combined, and cleaned for duplicates and incomplete entries (see flow diagram in Fig. 1). For the remaining articles, the title and abstract were screened and those excluded (sequentially), that first, did not utilise a combination of LCA and MFA, second, did not apply the method to a case study (merely theoretical framework), or third, did not perform a future-oriented study. The combination of MFA and LCA is hereafter defined as studies whose modelling uses both MFA and LCA, as opposed to studies that.

- use only one of the two methodologies,
- compare both approaches without modelling, or
- do not have modelling interlinkages between the two methodologies (e.g., different study object).

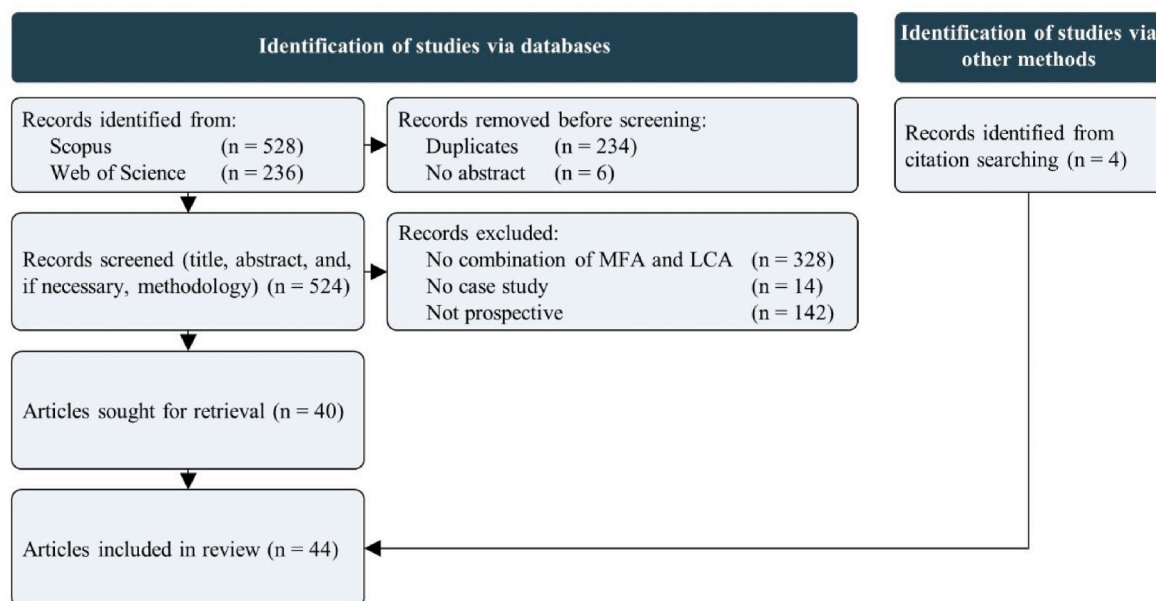


Fig. 1. Flow diagram of systematic review.

Theoretical frameworks that do not include case studies were excluded, because they are the clear minority and, depending on the level of detail, can be difficult to compare to studies that include case study applications. For example, they do not normally define a spatial or temporal scope of analysis.

According to the temporal dimension of the analysis, the publications can be grouped in retrospective or prospective. Retrospective studies are used to assess past policies and historical developments, but normally do not consider future developments. Retrospective studies are not deemed appropriate for ex-ante assessments of the impact of policies on the market. Therefore, and to limit the scope, we only included prospective studies, as these are considered directly applicable to the policy impact assessment process that deals with scenario-based evaluations of future development. In our study we define prospective studies as those that are future-oriented, by modelling future material flows and sometimes by considering future points in time in the life cycle inventory (foreground and background data). Within the prospective studies (which are all included in the analysis), we furthermore differentiate according to the temporal modelling approach between static and dynamic MFA (assessing one time increment compared to tracing changes in material flows over multiple time steps) and static and dynamic life cycle inventory data (keeping the inventory data constant over the study period or varying it and considering changes over time). It was not always easy to identify such prospective studies. Often, it is not clear from the title and abstract alone whether a study is retrospective or prospective. Some articles track material flows across the product lifetime without indicating the time horizon or year of analysis (e.g. (Aryapratama and Pauliuk, 2022; van Stijn et al., 2022)). If a present day analysis calculates the results over a 50 year span of product lifetime, it can be argued that the study is to a certain degree future-oriented. For such studies we assumed that they are prospective and included them in the review. Filtering studies according to their prospective character made a case-by-case evaluation necessary, and includes a risk of bias due to the qualitative nature of the assessment. Limiting the scope to prospective studies might exclude studies that are non-prospective but methodologically relevant, but we made a deliberate decision to limit the scope at this point.

To expand the spectrum, the final papers (particularly introduction and methodology section) were reviewed for additional citations that met the search criteria.

Full records were retrieved and reviewed according to the modelling approach (or type of combination). Furthermore studies were assessed according to the categories spatial scope, object of study, temporal scope, data and software usage, and by assessing the link between the study and the CE policy context and its applicability to the EU Ecodesign Directive impact assessment process.

3. Results

Of the 768 identified records (of which three papers were identified via citation searching), 44 were retrieved for the review process (see Fig. 1). The following subchapters summarise the findings according to the bibliometric information of the articles, object of study, the identified types of combinations, variations in spatial and temporal scope, the data and software usage, and their applicability for the assessment of CE policy strategies.

3.1. Bibliometric and spatial analysis and object of study

The earliest identified prospective study that applied the combination of MFA and LCA was published in 2003 (Yokota et al., 2003), but the large majority (80%) of articles were published in the three years prior to our analysis 2020 (11), 2021 (11), and 2022 (13), indicating that the combination of MFA and LCA has only recently received wider attention in the research field. Additional figures showing e.g. the number of publications can be found in supplementary information B. We found articles being published in 18 different journals, with almost half of the publications in three journals, namely the Journal of Industrial Ecology (11), Resources, Conservation and Recycling (7), and Journal of Cleaner Production (4) (Figure B3 in supplementary information). Prospective articles applying the combination of MFA and LCA were published by a total of 161 authors, of which 22 published more than one paper, and only five more than two.

Fig. 2 shows that, for the majority of analysed studies, the spatial scope comprises one entire country, such as China, where most country-scale assessments were conducted (Zhang et al., 2022; Chu et al., 2022; Di Dong et al., 2022; Ryter et al., 2021; Liu et al., 2020a; Liu et al., 2020b), or Japan (Morimoto et al., 2020; Kayo et al., 2019; Yokota et al., 2003). Within Europe, Norway (Lausselet et al., 2021; Sadeleer et al., 2020; Pauliuk et al., 2013; Sandberg and Brattebø, 2012; Venkatesh

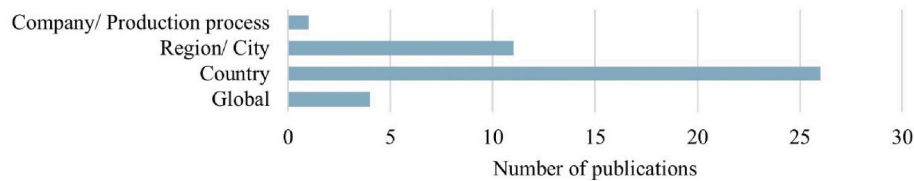


Fig. 2. Number of prospective studies applying the combination of material flow analysis and life cycle assessment (only those studies included where spatial scope was clearly defined). Studies on the EU are counted under the category country.

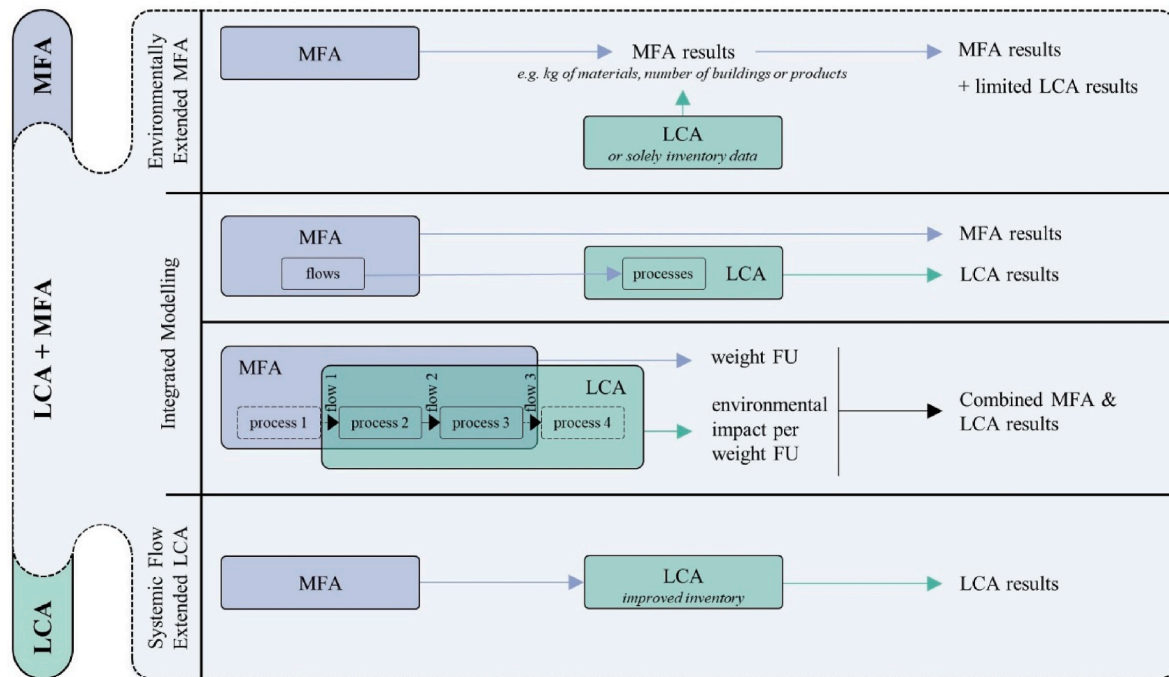


Fig. 3. Modelling approaches of prospective studies applying the combination of material flow analysis (MFA) and life cycle assessment (LCA) (referring here to both ISO standard environmental LCA as well as simplified environmental impact assessments based on life cycle thinking). FU = functional unit.

et al., 2009) and Switzerland (Wiprächtiger et al., 2022; Wiprächtiger et al., 2020; Heeren and Hellweg, 2019; Mehr et al., 2018) are the most frequently assessed study areas. The spatial scope is influenced by the location of the authors or research groups, and thus all the studies in the Norwegian context are (at least partly) driven by researchers affiliated with the Industrial Ecology Programme and the Department of Hydraulic and Environmental Engineering at the University of Science and Technology in Trondheim. Similarly, the studies on the Swiss context were conducted by researchers affiliated with the Institute of Environmental Engineering at ETH Zurich.

Second most common are region- or city-based assessments, especially for studies on the building sector or on waste management, e.g. a study on residential building stocks in Leiden (Netherlands) (Yang et al., 2022b), on the built stock in Melbourne (Australia) (Stephan et al., 2022), on solid waste management in Davao City (Philippines) (Olalo et al., 2022), or on the impacts of incineration phase-out on waste management in Madrid (Spain) (Istrate et al., 2021). Less frequent are studies on a global scale, e.g. (D'Amico et al., 2021; Pauliuk et al., 2021), and only one study was identified that focused on a production process (Ardolino et al., 2020).

The study object could most often be allocated to the construction or manufacturing sector, followed by the waste management sector. Within the construction sector, most studies deal with building stocks (e.g. (Yang et al., 2022a; Göswein et al., 2021; Lausset et al., 2021)), and some with building components or materials (e.g. (Malabi Eberhardt et al., 2021; Heeren and Hellweg, 2019)). For manufacturing, a wide

range of products are assessed by the studies, including traction batteries (Nguyen-Tien et al., 2022; Bobba et al., 2020), refrigerators (Velásquez-Rodríguez et al., 2021; Glöser-Chahoud et al., 2021), washing machines (Boldoczki et al., 2021), mobile phones (Glöser-Chahoud et al., 2021), and air conditioners (Yokota et al., 2003; Zhang et al., 2020). All of these products are either energy consuming or energy related, and thus fall under the scope of the Ecodesign Directive (even though batteries are regulated under a separate Directive (2006/66/EC) (European Commission, 2006) in the EU context). Interestingly, among studies that trace the flows of a single material across sectors, there is a strong focus on copper. Six studies were conducted on copper (e.g., (Zhang et al., 2022; Di Dong et al., 2022)), and only one on a different material, namely steel (Milford et al., 2013).

Further information on the study object and fields of application can be found in supplementary information B.3.

3.2. Modelling approaches

Different ways of combining MFA and LCA are conceivable and our systematic review confirmed that there is no one-fits-all approach, but instead a wide spectrum of combination types.

Based on our analysis, we classified modelling approaches of combined MFA and LCA according to their focus and level of integration into the three broad categories “Systemic Flow Extended LCA”, “Environmentally Extended MFA” and “Integrated Modelling” (Fig. 3). Needless to say, the boundaries of this classification are open and approaches may

have characteristics that could fit into different categories. We propose this classification merely to provide a better understanding of the characteristics and variations within the assessed studies and thereby to facilitate a discussion.

It should be noted that many authors are rather inconsistent when using the term LCA, also referring to it when conducting an environmental assessment that is not entirely in accord with the ISO standard (e.g. coupling unit process data from LCA databases with the results of an MFA). Thus, the term LCA in Fig. 3 can denote both a LCA conducted according to the ISO standard as well as different forms of simplified environmental impact assessments based on life cycle thinking (e.g. when items or requirements from the ISO standard are missing or it is unclear whether they have been considered, e.g. no specific notice is made of the four LCA phases or their concluding items, or the functional unit is not clearly defined).

These simplified environmental assessments are exemplified in the category of **Environmentally Extended MFA**, where the MFA results are complemented by a basic environmental assessment. No full LCA is conducted, and only environmental inventory data (or emission factors) are used to add an additional environmental dimension to the results. The clear focus of this approach is on the MFA. Without the LCA (or environmental impact assessment) part, the study would still function, but be less informative. In its simplest form, the MFA delivers the material flows, which are then linked with the background inventory data of LCA databases. The inventory data can refer to, e.g. material-related emissions (Lausselet et al., 2021; Yang et al., 2022b; Chu et al., 2022), energy-induced emissions (such as emissions of the electricity mix) (Glöser-Chahoud et al., 2021; Yang et al., 2022b; D'Amico et al., 2021), or process-induced emissions that contain several material or energy flows (Liu et al., 2020a; Milford et al., 2013). The environmental results often target greenhouse gas emissions and other impact categories are not part of the analysis. Furthermore, such analyses normally use static LCA inventory data without temporal changes (see 3.3).

Systemic Flow Extended LCA is similar to the previous category, but focuses on the LCA side. Here, the stand-alone results of the LCA are the primary goal of the study. It should be noted that an LCA according to the ISO standard (ISO 14040:2006, 2006) includes the data collection of relevant material and other physical inputs as part of the life cycle inventory. Practically speaking, every standard LCA includes an analysis of the material flows (compiling the inventory), i.e. an MFA. Under this premise, we could consider every LCA which uses dynamic and prospective material flows (e.g. via variable parameters in the modelling process) as a combined MFA and LCA. However, we only look at those studies that provide a clear distinction between the two methodologies. Systemic Flow Extended LCA under our definition is thus characterised by sequential modelling, in which the MFA provides the input for the inventory of the LCA and thereby a more systemic overview of material flows and easier parameterisation. For example, Aryapratama and Pauliuk (2022) perform an inflow driven dynamic stock modelling of wood use in Indonesia, and use the results as the input for the LCA model. All the research questions are related to environmental impact, so the objective of the study is clearly focused on the LCA part. A reversed but also sequential approach is used by van Stijn et al. (2022) and Malabi Eberhardt et al. (2021). Here, the authors first conduct the LCA to calculate the environmental impacts of different design options (over the lifetime), and then use the inventory data to do a more detailed MFA that provides macroeconomic implications such as the necessary imports and exports.

The highest level of integration is achieved, when the two methodologies are combined in one model, as **Integrated Modelling**. The majority of analysed studies fall under this category. Articles that follow this approach were marked by combined results and/or same system boundaries and/or using the same functional unit or flow object in both MFA and LCA. Without the respective counterpart methodology, the study would not (or less) function, and often the modelling is (at least partly) implemented outside of traditional MFA or LCA software (see 3.4

for software usage). Integrated Modelling can be done similar to the Systemic Flow Extended LCA in a sequential manner, where the MFA is conducted and provides the flows (of materials, energy, products etc.) which are fed into the inventory building of the LCA. In contrast to Systemic Flow Extended LCA, the results of the MFA are an integral and independent part of the results and are reported separately from the LCA results. For example, Velásquez-Rodríguez et al. (2021) first conducted an MFA to estimate the number of end-of-life refrigerators in Colombia, which serves as the input to calculate the impact of different end-of-life routes with LCA. Both the result of the MFA as well as the result of the LCA are presented. Similarly, Venkatesh et al. (2009) used a sequential modelling approach for wastewater pipeline networks in Oslo, Norway, in which the MFA served as the input for the LCA, but both MFA and LCA deliver independent results.

The more integrated type of modelling intertwines MFA and LCA. There is an identical or clear overlap in the system boundary of MFA and LCA, and/or the final results or goal of the study are a combination of the integrated modelling, based on the results of both MFA and LCA. Some examples are provided hereafter. Mehr et al. (2018) conducted a study in which they combine MFA with a modular LCA. In their study, a high-level MFA depicted wood use in Switzerland over a 200 year time horizon, and provides input and output flows of the processes (or modules), which are then combined with the LCA in a product-process-matrix. This matrix is then used as the basis for an algebraic optimisation model. Some of the same authors were also part of two later publications (Wiprächtiger et al. 2020, 2022) (research group at ETH Zurich, see 3.1) that applied a similar matrix based modelling approach, in which the MFA estimated the flows between processes and the LCA the environmental impacts of those processes. The final result, e.g. the optimal wood use strategy (Mehr et al., 2018), was a result of the integrated modelling. Within integrated modelling, the environmental assessment can, but does not have to, extend the scope of processes and material flows. Integrated modelling can be performed with identical system boundaries in a layered approach, in which the study object is disaggregated from e.g. the product to material, energy, and emission level. Each layer provides additional dimensions of information while results are consistent due to the common derivation (Pauliuk and Heeren, 2021). E.g. by tracking first the product flows and then disaggregating the information at material level by classifying material intensities for certain types of the assessed product (e.g. (Zhang et al., 2020)). For the building sector, a similar multi-layered approach can be used, in which material intensities are defined for different building archetypes (Lausselet et al., 2021).

Another approach was followed in a study from 2021, where Boldoczi et al. (2021) applied a combined MFA and LCA approach to assess washing machine reuse in Germany. The MFA is conducted to get the stocks of washing machines for each efficiency class per year. Then those results are combined with a modular LCA, in which each process is modelled separately. Both MFA and LCA have the same system boundary. However, the MFA excludes flows of resources and energy to/from the processes except the flow of washing machines. The results show the evaluation of different reuse targets and represent a symbiosis of the environmental impacts from the LCA and the dynamic tracking of flows (in this case products) over long periods of time derived from the MFA.

While it was not always possible to understand how closely MFA and LCA are integrated in a study, a clear indication of an intertwined modelling is provided if MFA and LCA are modelled combined in only one software application. E.g. Istrate et al. (2021), build an integrated model using MATLAB, to evaluate the municipal solid waste management of Madrid, Spain (more information on software usage in 3.4).

Several publications use multi-method analyses that included MFA and LCA, but additional methods as well, such as economic analysis (Brignon, 2021; Liu et al., 2020a; Liu et al., 2020b; Ryter et al., 2021), interviews to validate assumptions (Ryter et al., 2022), mathematical optimisation (Mehr et al., 2018; Olalo et al., 2022), regression analysis (Ciacci et al., 2020), nested systems theory (Stephan et al., 2022), or

criticality assessments (Bobba et al., 2020).

3.3. Temporal scope

One of our selection criteria was to only consider prospective studies (see chapter 2 for definition). On a side note, our analysis showed that most studies who conduct a future-oriented analysis do not use the term “prospective”.

Prospective modelling of material flows and life cycle inventory can be done static with discrete time increments (static MFA/static life cycle inventory data) or continuously over multiple time steps (dynamic MFA/dynamic life cycle inventory) (see Fig. 4).

While it is more common to assess dynamic material flows, there are studies that use static material flow, like Istrate et al. (2021), who compared the state of the waste management system in Madrid in 2017 to two prospective scenarios for the year 2025. More studies were identified using dynamic material flow while keeping the life cycle inventory data static. Pauliuk et al. (2013) conducted a study on the Norwegian dwelling stock (until 2060), in which they assume the upstream impacts to be constant over time (Pauliuk et al., 2013). While acknowledging that “the electricity mix in particular may change drastically in the future”, they calculate with the current energy mix mainly due to uncertainties about future development. D’Amico et al. (2021) follow a similar argumentation in their study on material substitution in building construction. They assumed static carbon coefficients over time, referring to “equally likely” scenarios for the increase and decrease of global carbon emissions until 2040. In their study on Swiss construction materials with a time horizon until 2055, Heeren and Hellweg (2019) kept the life cycle inventory data constant over time arguing that technological innovation was outside the study scope.

The most uncommon temporal modelling approach is to keep the material flows static while utilising dynamic life cycle inventory data. Studies using this approach are likely to be LCA-based studies that were not identified in our search query. However, the study of Ardolino et al. (2020) can be understood as a representative of this group. The authors calculated the static material flows for different thermochemical processes for the treatment of municipal solid bio-waste and used scenario-based variations of the electricity mix until 2030 when interpreting the results, while keeping the material flows constant. Finally, the combination of dynamic material flows and dynamic life cycle inventory data continuously models the material flows and the variations of the environmental inventory over time. Studies differ by which part of the life cycle inventory data are dynamic. In the simplest form, only one parameter of the background inventory data is dynamic.

Glöser-Chahoud et al. (2021), for example, coupled their MFA of different consumer products with dynamic greenhouse gas emission data of the average European electricity generation over time, and Zhang et al. (2020) analysed air conditioning in a Chinese city, creating scenarios with different annual decrease rates of the power grid emission factor. Environmental inventory data are also modelled dynamically by Di Dong et al. (2022) to assess China’s potential for reducing primary copper demand and the associated environmental impacts until 2100. Here, the authors considered changes in the electricity mix (background system) as well as in process efficiencies (foreground system).

The theoretically possible four different approaches of temporal modelling when combining MFA and LCA are illustrated in Fig. 4. Theoretically, it is possible to combine static MFA and static life cycle inventory data in a prospective manner, but this would always require at least two discrete time states to allow for comparison. With additional time steps, the approach can soon be classified as dynamic modelling.

Fig. 5 shows that the study period of the material flows ranges from comparing individual years to time spans of more than 100 years. There are several studies that (in addition to the prospective modelling) include a retrospective assessment to generate a production-based build-up of stocks or to have a base case and to ground scenario assumptions. Especially when assessing long-lived products, tracing the age of cohorts is decisive for determining the failure probability to estimate end-of-life flows, which constitute the stocks outflow. Velásquez-Rodríguez et al. (2021), for instance, designed their scenarios for the volume of end-of-life refrigerators in Colombia (as well as the lifetime function) based on historical waste collection data, and Liu et al. (2020a) based their estimations of end-of-life vehicles on the retirement of vehicles on the base year 2018.

How much the results depend on individual modelling parameters can be quantified using sensitivity analysis. Sensitivity can be defined as the fraction of relative change in the results over the relative change in the input parameter (Sadeleer et al., 2020).

For prospective scenario-based analysis, the results are highly dependent on the modelling assumptions. As expected, we found that the majority of studies (27) use and describe a sensitivity analysis to assess how changes in certain parameters influence the results (such as changes to the electricity mix, or process efficiencies over time), e.g. Boldoczi et al., 2021; Wiprächtinger et al., 2020). Most assessed studies conduct a scenario analysis in which they vary individual model parameters, such as product lifetimes (Glöser-Chahoud et al., 2021), collection or reuse rates (Di Dong et al., 2022), material or design choices (Göswein et al., 2021) or sociodemographic changes such as population growth (Pauliuk et al., 2013).

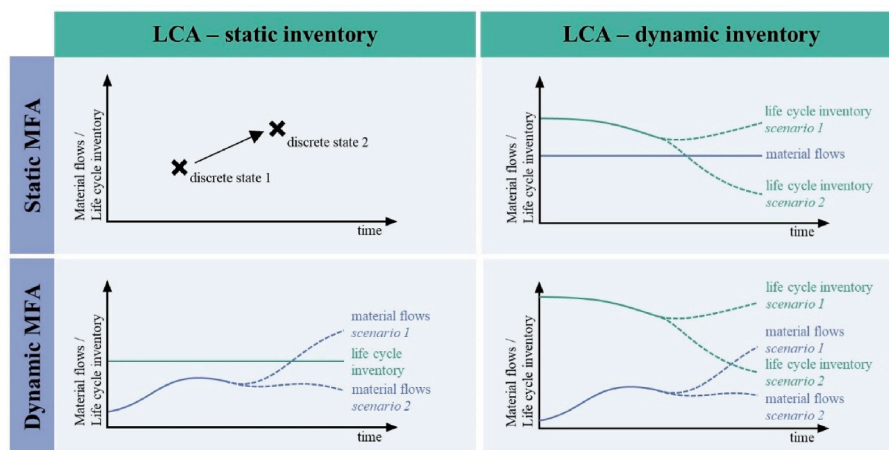


Fig. 4. Variations in static and dynamic temporal modelling of prospective studies applying the combination of material flow analysis (MFA) and life cycle assessment (LCA). Life cycle inventory refers to specific (e.g. process or material related) emissions in the background inventory data of the life cycle assessment. The curves are only indicative.

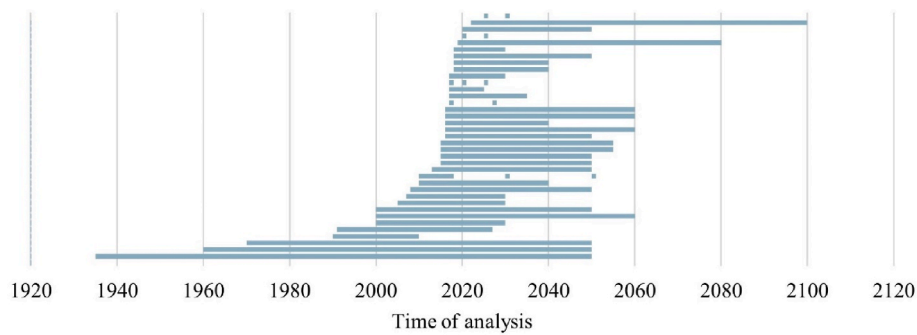


Fig. 5. Analysed time period of the material flows in prospective studies applying the combination of material flow analysis and life cycle assessment (excluded in the figure are studies that model scenarios using material/product lifespans without indicating a specific year).

3.4. Data and software usage

In our analysis, software refers to the programming environment in which the analysis was conducted, and data refer to the exogenous modelling inputs. Foreground data (for both MFA and LCA) are normally case specific and can be derived from a multitude of sources, such as field sampling, previous research studies or national statistics. In this study, we mainly focused on the background life cycle inventory data to analyse data usage.

Turning to the software used, we found that around half of the studies do not specify which software was used for the modelling process. Those that do specify the software can be differentiated in LCA-specific software, MFA-specific software, software that allows combined modelling, or combinations thereof. Several studies use LCA-specific software, such as SimaPro (Boldoczki et al., 2021; Ryter et al., 2022), openLCA (van Stijn et al., 2022; Malabi Eberhardt et al., 2021), or Brightway (Wiprächtiger et al. 2020, 2022). In contrast to LCA, the wider conceptual flexibility of MFA allows for more variation in modelling software, and thus purely MFA-specific tools, such as STAN (Wiprächtiger et al., 2020), are rarely mentioned in the studies. Instead, it is common to conduct the modelling in a flexible software solution, such as spreadsheets (Mehr et al., 2018; Olalo et al., 2022), MATLAB (Istrate et al., 2021), or Python (Boldoczki et al., 2021; Velásquez-Rodríguez et al., 2021; Aryapratama and Pauliuk, 2022). Several studies implement modelling (at least partly) outside of LCA-specific software by utilising modular LCA (Boldoczki et al., 2021; Bobba et al., 2020; Wiprächtiger et al., 2020; Mehr et al., 2018). Modular LCA is characterised as not modelling the entire system, but individual life cycle stages or processes (= modules), and only later combining those modules in a variable manner (Steubing et al., 2016). These modules can have wider system boundaries than single unit LCA processes. However, this requires a sequential approach where the environmental impacts of a module are first modelled in LCA-specific software and are then exported to another software environment to be integrated into the MFA. Using only unit processes extracted from LCA databases may allow modelling in a single-software solution.

Due to its more flexible nature, modular LCA can reflect the “broader level of abstraction often found in MFA models” (Mehr et al., 2018), and is “capable of reducing the effort involved in performing scenario analyses and optimisation when several key choices along a product’s value chain lead to many alternative life cycles” (Steubing et al., 2016). Technically, LCA-specific software allows the calculation of different alternatives using parameters, but the modelling flexibility for a high number of scenarios with varying multiple parameters over long time scales is limited, and researchers therefore have shifted to other modelling environments.

In terms of data usage, many studies did not specify or did not use data from life cycle inventory databases. Of those that did, the large majority (20 studies) used some version of the Ecoinvent database. Sometimes the Ecoinvent data were complemented, e.g. with other

inventory databases such as EPiC (Stephan et al., 2022), reports from intergovernmental organisations such as the Intergovernmental Panel on Climate Change (IPCC) or the International Energy Agency (IEA) (Ciacci et al., 2020; Olalo et al., 2022), or governmental statistics (Sevigné-Itoiz et al., 2015; Olalo et al., 2022).

3.5. Applicability for the assessment of circular economy policy strategies

Before discussing the results in terms of their applicability to the ecodesign impact assessment process, it is interesting to see whether the studies assessed are already being used in the CE policy-making process, either by evaluating the effect of potential policies, or by providing policy recommendations based on the study results.

Di Dong et al. (2022), for example, state several specific policy implications of their results and the analysis by Ryter et al. (2021) estimates different regional policy change scenarios. CE requirements can be differentiated into the CE strategies of reducing, reusing and recycling (3Rs), all of which are present in current Ecodesign regulations (Barkhausen et al., 2022). In our analysis, we identified studies that consider all three strategies (e.g. (Di Dong et al., 2022)), but found a clear focus on the assessment of measures related to recycling (38 studies), followed by reuse (16 studies) and reduce (10 studies). Examples of assessing primarily recycling strategies include Velásquez-Rodríguez et al. (2021), who assess the roll-out of a nation-wide refrigerator-recycling program in Colombia called “Red Verde”, and Sadeleer et al. (2020), who assess different recycling rates of household food waste. Studies evaluating the impacts of reuse strategies include Boldoczki et al. (2021), who conduct their study on washing machines in Germany to measure “long-term implications of policy decisions”, such as the effect of implementing a 5% target for preparation for reuse. The least number of studies assess options related to reducing material consumption (e.g. sufficiency strategies or sharing concepts), and this is often only assessed in addition to measures related to recycling and/or reuse. A study that can be classified as reducing was carried out by Glöser-Chahoud et al. (2021), who assess the influences of extending product lifetime on the environmental performance of refrigerators and mobile phones. However, when considering lifetime extension due to repair and not design choices, this could be counted as a reuse strategy. Based on our findings in the previous sections, we will now turn to their implications for the ecodesign policy-making process.

4. Discussion

Already in 2000, Haes et al. (2000) stated that MFA and LCA are independent research communities, “separated rather by historical than by methodological lines”. Since then, a variety of prospective studies that apply the combination of MFA and LCA have been published, with large variations in the modelling approach used. Our analysis provides an overview of existing approaches, in particular their applicability to product policy impact modelling, and also classifies existing approaches

into three distinct categories. Environmentally Extended MFA was found to be a simple and practical approach, because it avoids going through all the formal phases of an LCA study, and can be conducted without LCA expertise. However, this carries the risk of a lack of proper understanding of the environmental data of flows and processes, which might lead to oversimplification and wrong conclusions (and in turn reduce trust in the reliability of environmental assessments). Such analysis should always be based on a thorough understanding of LCA theory and the reliability of the life cycle inventory data. The problem of LCA studies not conforming to the ISO standards, or ambiguities within the standards, has been highlighted before (Schaubroeck et al., 2022; Heijungs et al., 2021; Schrijvers et al., 2016)). MFA, in turn, is a less standardised methodology, and other researchers have pointed out that the definition, including the methods used under the term MFA, are not always clear in the literature (Baars et al., 2022).

Systemic Flow Extended LCA can be a way to enhance the LCA by considering wider system boundaries and systemic interactions of material flows. And Environmentally Extended MFA can be a way to add an environmental layer to physical material flows. A similar concept has been framed by Pauliuk and Hertwich (2016) as extended dynamic MFA, where MFA is extended with product life cycles in a multi-layered way.

Integrated modelling approaches are most frequent, which simultaneously apply MFA and LCA (or simplified environmental impact assessments based on life cycle thinking) within one combined modelling environment and can provide multi-dimensional results. We found different hybrid software solutions but also a trend towards the use of flexible software solutions. Integrated modelling approaches seem to benefit from conducting the analysis outside of LCA specific software by using e.g. Python instead. This offers higher modelling speed and flexibility to combine changing processes with dynamic flow parameters, and to easily modify the study design. When conducting such a study not using LCA specific software, using modular LCA can help to avoid the modelling constraints of traditional LCA software.

Regarding the spatial scope, our analysis provides detailed insights and shows that studies at the country or regional level are most frequent. This is in line with the observation of Baars et al. (2022), who used the broader metric of micro and meso level to group integrated MFA studies. The majority of the studies they analysed fall into the meso scope, which includes the country level and local regions such as cities and neighbourhoods. This observation may stem from the characteristics of MFA and LCA regarding spatial scope. LCA is a function-based methodology that considers all the flows and processes required to provide the service or function of interest, therefore normally the geographical scope follows the function. MFA, on the other hand, is often conducted within a clear geographical boundary. In a combined MFA and LCA, the LCA often uses a pre-defined spatial boundary. With regard to the evaluation of CE policies, upscaling and the clear geographical boundary are both needed to assess the implications of certain measures for e.g. one defined country.

The temporal dimension was found to be a critical demarcation point between studies. Most of the reviewed studies model the material flows dynamically (e.g. (Velásquez-Rodríguez et al., 2021; Boldoczki et al., 2021; Huang et al., 2020)), but within the LCA part, there are large differences in terms of accounting for changes over time.

If the LCA foreground and background data are static (remain unchanged over time), then it is easier to combine MFA and LCA in a decoupled manner (e.g. (D'Amico et al., 2021; Sadeleer et al., 2020; Heeren and Hellweg, 2019)). However, if changes to material flows over time are combined with changes in e.g. process emissions over time, then an integrated MFA and LCA study is needed to evaluate scenario results, as MFA and LCA results are interdependent (e.g. (Ryter et al., 2022; Di Dong et al., 2022; Seigné-Itoiz et al., 2015)). The tendency to not discuss temporal aspects in the inventory when conducting LCA has been noted by Resch et al. (2021), who used a dynamic LCA approach to model environmental impacts in the building sector. Considering dynamic environmental impacts such as lower future emissions due to

technological progress can provide more multi-faceted results at the cost of greater uncertainty. Furthermore, dynamic (time-dependent) inventory data is commonly not available in standard LCA datasets such as Ecoinvent and thus can require substantial additional data collection efforts and might be prone to higher uncertainties. Data collection efforts are a relevant concern, and the problem of low quality and quantity of inventory data is a known issue also noted by Islam and Huda (2019). Especially in the field of MFA, there are few inventory databases compared to LCA (Birat, 2020), and our results confirm this: where secondary databases are mentioned, the majority are LCA based (mostly some version of Ecoinvent),

Corona et al. (2019) identify MFA and LCA as two of the three “backbone” frameworks for CE assessment (input-output analysis being the third). Going beyond this, our results showed that the combination of MFA and LCA is also suitable and commonly used in the context of CE policy-making. Combined MFA and LCA approaches are applied across sectors, including energy-consuming and energy-related products that fall under the scope of the Ecodesign Directive.

Several requirements can be defined for assessing the potential impacts of CE measures under the EU Ecodesign Directive, all of which can be well covered by combining MFA and LCA (see Table 1): Stock modelling needs to move from the product to the material level, and environmental assessment should cover life cycle stages beyond the use phase to evaluate recycling strategies. The analysis needs to be applicable to energy-using and energy-related products, cover the spatial scope of the EU (and beyond if certain life cycle stages require it) and be prospective to assess scenarios over long time periods.

As our analysis has shown, existing approaches are able to fulfil these requirements. In addition, the use of data and software for impact assessments should be simple and comprehensible and allow the use of the same modelling environment for different product groups. As complexity increases (e.g. due to the consideration of additional life cycle phases, extended lifetimes or the tracking of individual materials), the effort required for data collection increases. We have seen a variety of modelling approaches to combine MFA and LCA, making it difficult to generalise about the complexity of modelling. The approaches are often case study specific and there is a correlation between the level of detail of the analysis and the complexity. In principle, the combination of MFA and LCA provides a toolkit for assessing aspects of the CE in the context of ecodesign product regulations that combines the individual strengths

Table 1

Ability of material flow analysis (MFA), life cycle assessment (LCA) (considering current usage), and combined approaches to meet requirements for impact assessments of circular economy requirements under the Ecodesign Directive framework (well (++), moderately (+) or not (–) meeting requirements).

	Requirements for impact assessments in the Ecodesign Directive context	MFA	LCA	Combined MFA + LCA
Circular economy requirements	Tracing individual material flows across product lifetime	++	+	++
	Estimating environmental performance (beyond the use phase)	–	++	++
Spatial scope	Clear geographic boundary (regarding product sales in EU market)	++	+	++
Temporal scope	Dynamic and prospective (scenarios over long periods)	++	+	++
Data and software usage	Flexible and transparent, with readily available software and datasets (currently Excel-based)	+	+	+
Sectors of application	Sector not explicit, energy-using and energy-related products, and beyond under the proposal for Ecodesign for Sustainable Products Regulation	++	++	++

of MFA and LCA.

The combination of MFA and LCA is well suited to compare not only the environmental impacts of static product design alternatives, but also to consider the impacts of CE measures on product and material flows over time with high granularity. Combined approaches allow optimisation at system level by combining the detailed function-based approach of LCA with the broader MFA perspective. Integrated modelling can increase flexibility and provide multi-dimensional results with high granularity, moving away from the sequential approach in ecodesign of conducting an environmental assessment of the design options with the EcoReport tool and an independent stock model. An adaptation of the current approach is needed to assess the requirements of the CE by moving from the product to the material level and focusing more on the life cycle phases beyond the use phase. The diversity of integrated modelling approaches provides the opportunity to meet the changing requirements.

Dynamic LCA inventory is expected to greatly impact long-term scenario results and it seems pertinent to at least consider its usage for certain parameters. There is, however, a trade-off between the level of detail versus modelling complexity and data collection efforts, which could be mitigated to some extent by conducting upfront sensitivity analyses to identify the most relevant study parameters and only keep these dynamic.

It remains to be seen how well the update of the MEErP can deal with the new requirements that are created by the stronger consideration of CE requirements in EU product regulations.

A number of important limitations need to be considered. First, our systematic literature review could have missed publications that do not refer to the terms MFA and LCA. Studies that combine MFA with environmental impact assessments without conducting a full LCA might have not used the keyword LCA and consequently could have been missed by our systematic search. Conversely, our findings showed that many studies use the term LCA very liberally, even when it is not apparent that the required steps of the ISO standard have been followed. The spectrum of what is considered LCA varies widely among the studies. Therefore, it must be highlighted that in our classification of combined LCA and MFA approaches, LCA refers to both ISO standard analysis and simplified (life cycle thinking based) environmental assessments. It can only be emphasised that a clear understanding of what constitutes LCA should be a prerequisite for labelling one's analysis LCA. As our analysis has shown, the fields of LCA and MFA are increasingly merging which makes it even more important to be consistent in nomenclature and classifications to avoid misunderstandings.

Secondly, due to the high number of identified sources and manual sorting, studies that meet the selection criteria (combine MFA and LCA, are prospective, and include a case study) could have been falsely sorted out if this information was not clear from their title and abstract. In addition, articles were sorted out that did not meet the selection criteria (e.g. not prospective), but which could have been relevant from a methodological point of view.

Thirdly, the classification of the articles by categories such as spatial scope or sector of application contains ambiguities, as some studies have cross-category characteristics. The corresponding figures should therefore be treated with caution. Our analysis focused on the combination of MFA and LCA, and while we identified several studies that combined these two approaches with additional methodologies such as economic analysis, we did not assess these combinations in detail. Of particular interest could be to investigate the combination of MFA and LCA with input-output analysis (e.g., environmentally extended input-output analysis), for top-down assessments of material flows and environmental impacts across economic sectors. Thinking beyond mere environmental impacts, life cycle sustainability assessment comes into consideration. Especially when evaluating CE policies, the social and economic impacts could be considered and included in further analysis.

Researchers should also look at how to improve the flexibility in LCA-specific software or how to develop software that includes

modelling interfaces for both MFA and LCA.

5. Conclusions

Our systematic review identified 44 scientific publications of prospective studies using the combination of MFA and LCA, with varying levels of integration of the two methodologies, geographical and temporal scope and fields of application. We found sequential modelling approaches that lean either on the LCA side if the inventory modelling in LCA is improved by conducting an upfront MFA, or on the MFA side if the results of the MFA are extended by a basic environmental assessment. However, the majority of studies use integrated modelling where both MFA and LCA are essential for the study's objective and the modelling is often implemented in one software. Most studies are conducted in the European context, and there is a focus on country-scale assessments. The time scale varies greatly from comparing discrete years to continuous modelling of periods longer than 100 years. Most studies use dynamic MFA (material flows change over time) and it is less common to see a dynamic approach in the life cycle inventory. Prospective studies that combine MFA and LCA are applied across sectors, including construction (buildings), manufacturing (especially energy consuming or related products) and waste management. Almost all studies have a clear link to the policy making process, and the combination of methodologies features many characteristics that make it suitable for impact assessment modelling under the EU Ecodesign Directive.

Our research is novel and to the best of our knowledge provides the first in-depth overview of studies combining MFA and LCA and their applicability to the CE policy context based on the example of the Ecodesign Directive. We revealed the different combinations used and, based on our results, suggest that researchers in this field should further explore integrated one-software modelling with dynamic material flow and dynamic life cycle inventory.

Our results have important implications for researchers and policy makers. The combination of MFA and LCA shows suitable characteristics to assess the multidimensional domain of CE policy, especially in the context of the Ecodesign Directive. It can scale-up the robust environmental assessment of LCA by considering the complex interactions of material flows over long time periods and large spatial scopes of MFA. Compared to the alternative of conducting separate MFA and LCA, integrated approaches create more interdependencies that can reduce flexibility and increase uncertainty due to the complexity of modelling and data collection. In return, the integrated approaches promise increased information value, improved consistency of results, and a more robust basis for decision-making.

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CRedit authorship contribution statement

Robin Barkhausen: Conceptualization, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Leon Rostek:** Conceptualization, Writing – original draft, Writing – review & editing. **Zoe Chunyu Miao:** Conceptualization, Writing – original draft, Writing – review & editing. **Vanessa Zeller:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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